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PROBABILISTIC SYSTEMS MODELING AND COST/PERFORMANCE METHODOLOGIES FOR OPTIMIZATION OF VEHICLE ASSIGNMENT

FINAL REPORT

VOLUME 1

TECHNICAL DESCRIPTION

31 MARCH 1971

PREPARED UNDER CONTRACT NAS2-5202

FOR

ADVANCED CONCEPTS AND MISSIONS DIVISION
OFFICE OF ADVANCED RESEARCH AND TECHNOLOGY
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER
MOFFETT FIELD, CALIFORNIA

BY

LOCKHEED MISSILES & SPACE COMPANY
SUNNYVALE, CALIFORNIA

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FOREWORD

This report volume describes the analytic methodology and model development of a computer program for probabilistic, optimal assignment of launch vehicles and related program elements to advanced space missions. This study is being performed for the National Aeronautics and Space Administration under Contract NAS 2-5202. The study is monitored by Mr. R. E. Slye and Mr. Harold Hornby of the Advanced Concepts and Missions Division of the Office of Advanced Research and Technology.

Individuals of Lockheed Missiles & Space Company, Sunnyvale, California, who contributed to this study are L. F. Fox, project leader; C. J. Golden, key technical member; and W. T. Lew.

ABSTRACT

The optimal, least cost assignment of launch vehicles and related program elements for a total space program over an extended time period requires the solution of a large combinatorial problem. Using an accelerated search technique, this problem was solved in prior work on a deterministic basis. The conversion of this comprehensive space program evaluation tool to a probabilistic model is the primary objective and result of this study. The developed computer model retains the capability for deterministic solutions but adds a new, powerful dimension for probabilistic evaluations and sensitivity analyses. With statistical data input, the program can output program costs quantified to any degree of certainty. The input/output structure is versatile with multiple options to adapt the program to the needs of the analyst. Using one option, output results can be smoothed under variable year-to-year budget constraints which reflect external economic conditions including growth and inflation. While applied to space systems in this study, the developed technique and basic model can be adapted to other optimal assignment problems by particularizing the parameters to the new problem.

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SUMMARY

This document is Volume 1 of a two volume report entitled Probabilistic Systems Modeling and Cost/Performance Methodologies for Optimization of Vehicle Assignment. Volume 2 provides details on the computer program developed during this study. This volume provides a technical description of an analysis of historical data, the development of the analytical approach, and the capabilities of the developed computer model.

Building on a deterministic model developed under prior work, the conversion of this comprehensive space program evaluation tool to a probabilistic model is the primary objective and the major result of this study. Using a significantly modified branch-and-bound technique for accelerated search, the model evaluates the data from all combinations of launch vehicles and other interrelated space program elements, and selects a global optimum, least cost total space program for a specific mission profile. The model has multiple input and output options responsive to the needs of the analyst; these include stage matching to form vehicles, performance and time availability for vehicle-to-mission screening, and budget smoothing under various ceilings and external economic conditions. Expendable, partially reusable, and fully reusable vehicles may be evaluated in the same program mix.

Analysis of historical data clearly shows there are predictable cost uncertainties in data which apply to advanced space systems having technological risk. The log-normal distribution was identified as most appropriate for the analytic relationships in this model. The model retains the capability for deterministic solutions but adds the new, powerful dimension of probabilistic evaluations and sensitivity analyses, which quantify the cost uncertainties known to exist in high technology, advanced space programs.

The model can be applied to a wide range of space program evaluations — to macro-problems which evaluate various options of total space programs, to intermediate

problems which analyze separate portions of a space program (e.g., optimizing a scientific, exploratory, service satellite program within a total space program), and to micro-problems (e.g., determining the cost optimal subsystem among several alternates for a given space vehicle). In all cases the impact of cost uncertainty can be quantitatively assessed.

In this application the optimal assignment model is applied to space systems. However, the technique can be readily applied to diverse optimal assignment problems by particularizing the parameters to the new problem.

Section 1
INTRODUCTION

1.1 BACKGROUND

During a preceding phase of work under contract NAS2-5202 (directed by the NASA Advanced Concepts and Missions Division) a deterministic computer model was developed for the analysis and optimal assignment of launch vehicles and other program elements that comprise a multi-mission space program over an extended period of time. This analytical tool quantitatively evaluates the many interrelated factors which enter such a large-scale problem. The computer model incorporates optional performance subroutines that determine vehicle-to-mission compatibility, evaluate the capability and time availability of supporting elements (such as launch sites and pads), and, most important, employ an accelerated search technique to determine optimal solutions based on least cost.

The numerous functional options readily selectable by the user provide flexibile adaption of the model to the needs of the analyst. A capability to output optimal assignments that are smoothed under parameterized economic conditions including variable budget ceilings, with growth and inflation factors, is one option available. Using these options, various candidates may be evaluated for space transportation systems including fully reusable, partially reusable, and expendable systems as elements of a total space program mix.

Additional details on this deterministic model are provided in Ref. 1.

1.2 OBJECTIVE AND TASKS

Prior analyses of advanced systems data have shown that there is considerable variability between planning cost estimates and costs actually experienced in developing new

systems and making them operational. This variance is particularly notable in high technology systems involving state of art advances.

Within limitations the impact of relatively simple variability in input data can be analyzed by iterative means using a deterministic model. However experience using this approach has shown that determination of the uncertainties involved in the evaluation and the optimization of realistic advanced programs requires a very large number of iterations. Further, the dependence between entering variables, as detailed in section 3.3, has significant effect on solution outcomes but cannot be handled on a deterministic basis.

The objective of the present phase of effort, therefore, has been the conversion of the deterministic assignment and budget smoothing model to a probabilistic model. The converted model is to accept probabilistic inputs, perform internal analysis and optimization, and provide outputs with their associated measures of certainty.

During this phase of effort the above objective has been accomplished by effort under three basic tasks. A brief description of these tasks follows.

1.2.1 Statistical Analysis of Data

Historical data were analyzed on a preliminary basis to determine statistical characteristics of the data. Results of this analysis provided a basis for a tractable solution to a problem of this magnitude (i.e., the feasibility of an analytic, probability density function approach rather than one using random numbers, e.g., Monte Carlo). This analysis also determined preliminary values for statistical parameters which may be used in computer program input.

1.2.2 Analytic Approach

Using the results of the preceding task an analytic approach was developed which solved this large scale problem while maintaining relatively short computer run times and

remaining within computer storage constraints. The logarithmic normal (log-normal) probability density function was identified for use in the analytic relationships. This density function possesses the characteristics required by such a cost growth distribution function and, since the log-normal distribution is functionally related to the normal distribution, statistical relationships of interest to the user are easily derived and computed.

Using the log-normal distribution, analytic relationships were developed for use in the probabilistic model. From the input of most likely and upper tail values, expected values are derived for use by the optimizing algorithm. The statistical parameters involved in each assignment, including the dependence between these variables, are used to determine uncertainties associated with each assignment, and probabilistic relationships between assignments.

1.2.3 Computer Program Development

In developing the probabilistic computer model, the deterministic model described in section 1.1 was embedded within the new model which includes the analytic relationships developed above. Short run times and minimum storage requirements were maintained, permitting production use of the program in a multi-user computer system. Because considerable emphasis was placed on flexibility, selectable options are available to match the model to varying needs of the user. Some of the options which generate this flexibility are as follows:

- Optimized assignment (least total cost which meets mission requirements) of space program elements, e.g., stage hardware, launch sites and pads, stage integration, reusables, and others. Alternately a predetermined assignment may be input and smoothed if desired.
- Optimization with or without budget smoothing under year-by-year budget constraints.
- Variable economic conditions — budget ceilings, support bases, inflation — may be imposed over an input period of time.

- Assembly of vehicles from input stages considering physical and performance parameters (both variable); evaluation of alternative components on same stage.
- For reusable stages, a given number to be procured may be input or the model will compute the required number based on actual launch rates.
- For reusables, capability for payload to be delivered in a single or multiple launches (modularization).
- Several levels of vehicle-to-mission screening are available. The most comprehensive includes type of stabilization, man-rating, number of required restarts, launch site, and payload vs. V_{ch} requirements.
- Length of space program selectable, from 1 to 20 years.
- The development period may be stretched or accelerated during the smoothing process at the option of the user. Otherwise the input nominal development period is maintained.
- Recurring cost dependence on learning rate may be selected from two types in wide use or bypassed as desired.
- The deterministic model is available by leaving out all probabilistic input. All calculations based on these input data are then bypassed automatically.

The wide range of input acceptable to this model and the wide range of output available from the model make it particularly useful as an evaluation tool. Some of these features are listed below.

- Evaluating expendable, partially reusable, or fully reusable stages/vehicles mixed in the same total space program.
- Determines whether a stage/vehicle, launch pad, stage integration, etc. has been developed and is available when needed; if not, provides for development on a timely basis if feasible.
- Pro-ration of all types of costs when there is multi-mission use of a program element (i.e., family or shared costs).
- Output of program cost based on most probable (modal) values, on expected values, or on values such that the residual probability of cost overrun is less than xx%.

- Output includes probability that the total cost of space program A will be ≤ cost of program B, so comparisons may be made between competing assignments. For the optimal assignment, mean, modal, and 50% uncertainty intervals are plotted for each year's spending level.

More complete details on input options and other program adaptations are provided in Section 4 and in Appendix A (Vol. 2).

1.3 GENERAL MODEL DESCRIPTION

As summarized, the probabilistic model solves the same large scale combinatorial problem, including multiple interrelated program elements, as the previous deterministic model (Ref. 1). For example, finding the optimal assignment of 25 candidate vehicles to 500 missions over a 20-year period leads to a problem having possible solutions on the order of 25^{500}. In addition, the new model handles the various cost factors on a probabilistic basis. As before, factors are handled explicitly, so a global optimum solution is assured. The major difference between the two models is that input costs, based on a statistical analysis of historical data, are entered as parameters of probability distributions, are appropriately analyzed on this basis within the model, and results are output with solution certainties (or uncertainties as desired) quantitatively specified.

In addition to this large scale optimal assignment problem the model analyzes many other important aspects of a total space program. Internal model analyses, typical of the total spectrum available to the user, have been indicated in section 1.2.3.

Figure 1-1 graphically illustrates selected functions within the model. Considering the major flexibility of the model and its options previously outlined and discussed in more detail in the following sections of the report, this figure and the related discussion

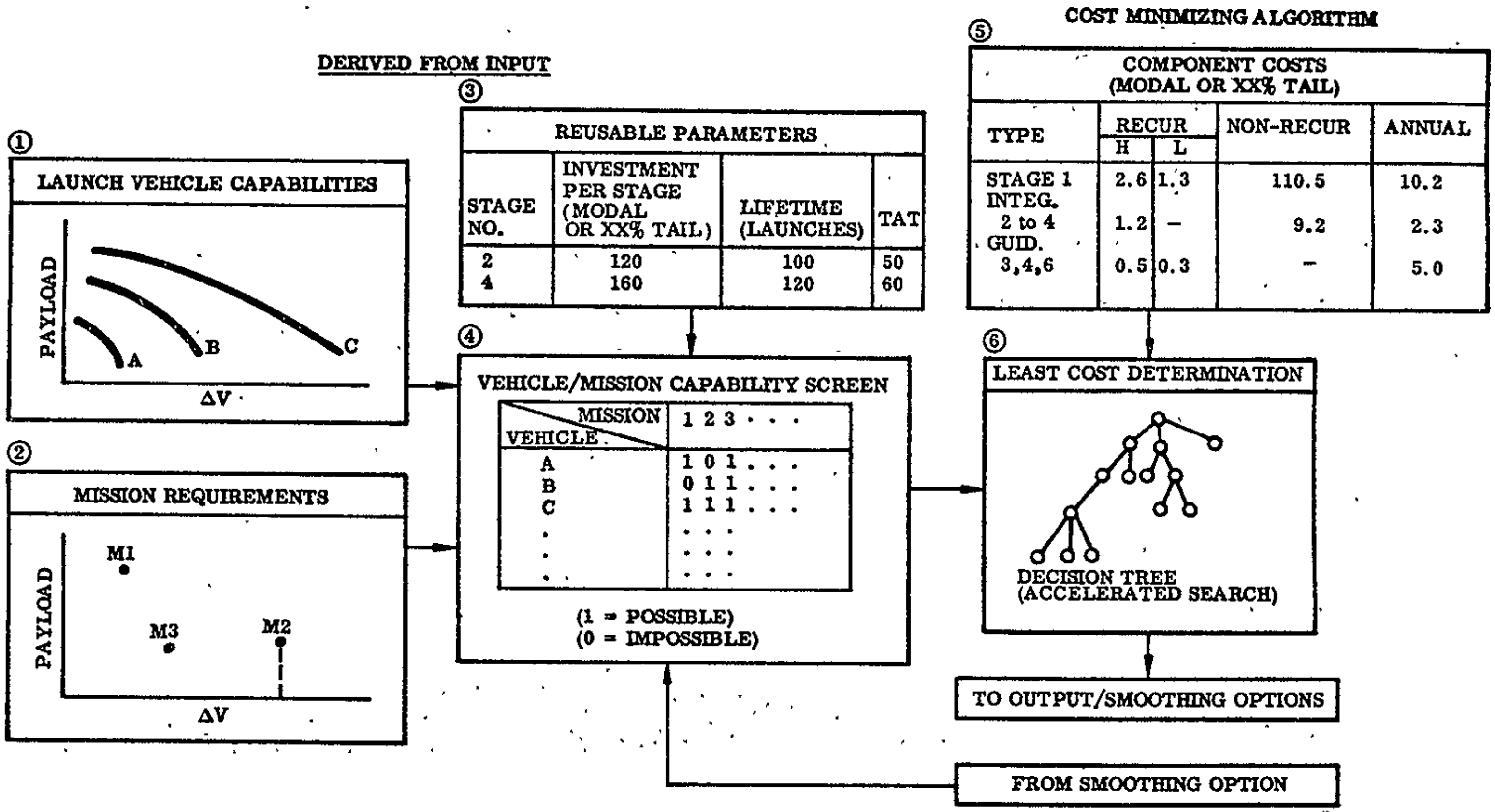


Fig. 1-1(a) Optimum Assignment Model

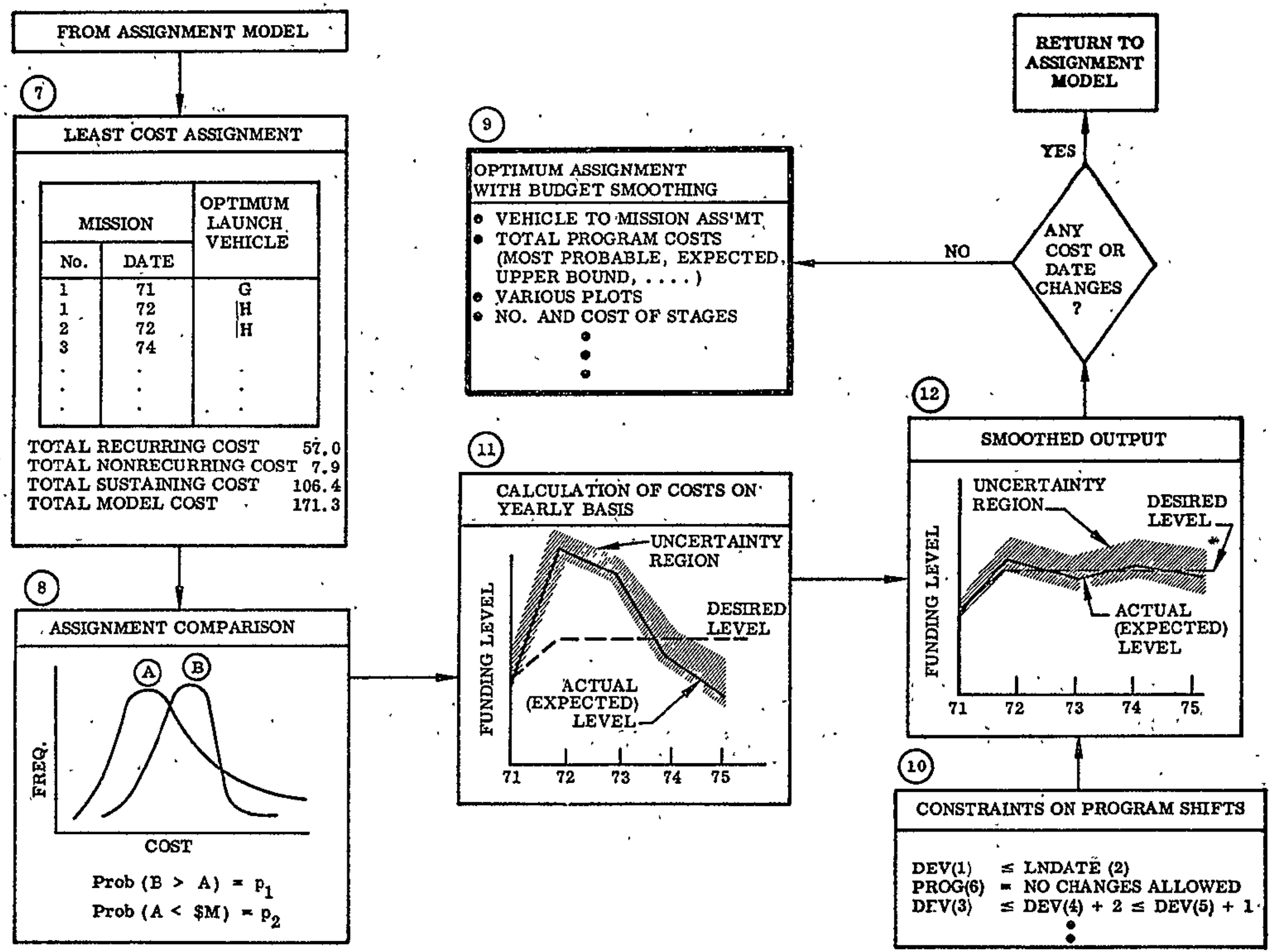


Fig. 1-1(b) Output and Smoothing Options

should only be considered as representative of the many capabilities and functions which are available. Selected comments applicable to this figure follow:

- Items 1, 2, 3, and 4 represent input or internal computations derived from input. It is notable in 1 that launch vehicle Δv performance is computed in the model as needed to save storage rather than through the use of "look-up" tables.
- In items 3 and 5 (and elsewhere as appropriate in the model) costs are input probabilistically. Item 5 indicates the three basic groups into which cost elements are catagorized for least cost determination in the accelerated search subroutine. "H" refers to hardware costs and "L" to launch and other related support elements. "Annual" costs are those computed on a yearly basis for "sustaining" purposes. Reusable stage programs have investment costs associated with them in addition to the conventional three categories. Item 3 reflects the special treatment investment costs receive which permits analysis of both reusables and expendables in a total program mix.
- Item 6 is a significantly modified branch-and-bound technique which provides an accelerated search of the solution space and outputs the optimal solution for the large scale combinatorial problem previously described.
- Items 7, 8, and 11 indicate types of output available for optimal space programs which have not been smoothed under some selected budget ceiling. In item 8, A is the optimal assignment while B is an alternative suboptimal assignment. Under realistic conditions, however, it is normally desired to examine space program options which are both optimized and bounded by varying budget limits. When the budget smoothing option is selected, item 10 indicates types of constraints which may be imposed.
- Item 9 represents the wide range of available output options (see section 4.5) and 12 illustrates an example of one of these options. In 12 the smoothing option has been selected.

The foregoing provides a general description of the model, its versatility, and some of its solution techniques. Note that the model can be applied to a wide range of space program evaluations — to macro-problems that evaluate various options of total space programs; to intermediate problems that analyze separate portions of a space program

(e.g., optimizing a scientific, exploratory, service satellite program within a total space program), and to micro-problems (e.g., determining the cost optimal subsystem among several alternates for a given space vehicle). In all cases the impact of cost uncertainty can be assessed quantitatively.

Section 2
STATISTICAL ANALYSIS OF DATA

One of the important problems in developing a model whose output is to be used as a basis for evaluating tradeoffs concerning future expenditures is the reliability or confidence in the cost estimates used as input to the model. When applying estimates to specific decisions, the evaluator must be cognizant of the uncertainties that exist in the estimated data. Further, to realistically plan programs that can be completed within budgetary constraints, he must be able to rapidly and quantitatively assess the impact of potentially significant changes in costs in ranking alternatives and making final selection of preferred candidates.

This section describes an analysis of data sources that apply to advanced systems to (1) identify error sources, (2) indicate their relative contributions to total error, and (3) indicate statistical characteristics of these error sources.

2.1 HISTORICAL ANALYSIS OF TRENDS

To determine the characteristics associated with the uncertainty of predicting costs, RAND (Ref. 2) introduces a classification of factors that affect success. These four classifications are as follows:

(1) Costs (development and production)
(2) Performance
(3) Time of availability
(4) Utility

Performance is used here to include all the qualities of any system that contribute to its utility, e.g., available velocity vs. payload characteristics, maintainability, reliability, payload capability to a given ephemeris, etc.

As used in this classification, utility is largely qualitative in nature, so the future utility or benefit of a system is not directly included in the program at this time. The analyst may investigate some consequences of utility changes by performing a sensitivity analysis on the mission model. The remaining three factors are largely quantitative in nature and, in practice, tradeoffs among these three are usually possible. A given performance normally can be attained earlier if greater costs are incurred, or, for given costs, earlier availability is possible if lower performance is accepted, etc. The relevance of these tradeoffs to development prediction is obvious — the selected parameter may be achieved at the sacrifice of either or both of the other two parameters.

The Assignment Program assumes initially that performance and availability time are fixed. Only costs are uncertain. While adjusting the rate of actual expenditure to accomplish on overall space program within realistic budgetary constraints, the smoothing section of the integrated vehicle assignment and budget smoothing program may change availability dates, but not performance characteristics. Historical data show that this approach represents a realistic situation in launch vehicle programs. Since great emphasis is placed on performance requirements, usually cost and/or availability give ground before performance is degraded. Often reliability is less than expected, but the amount by which other performance falls short is usually small in comparison to time extensions or cost increases incurred. Since budget constraints as they apply to programs continue to be quiet stringent, major emphasis has been given to uncertainties in cost estimates.

Uncertainties associated with cost estimates fall into the following three general categories:

(1) Uncertainties due to errors in the costing of the configuration supplied to the cost estimator (i.e., the intrinsic error in cost estimating)
(2) Uncertainties due to changes in the configuration (e.g., contract change notices (CCNs) as development progresses) (Program Uncertainty)
(3) Uncertainties caused by one or more unexpected changes in national economic conditions (Economic Uncertainty)

References 3 and 4 detail the five following causes of cost escalation in aircraft and missile development:

(1) System performance change accounts for approximately 22% of overruns
(2) Schedule change ... ~ 6.3% of overruns
(3) Engineering change in order to meet original performance requirements ... ~ 10.6% of overruns
(4) Economic change ... ~ 15.4% of overruns
(5) Cost estimate revision ... ~ 45.6% of overruns

Causes (1) through (3) fall into category 2 uncertainties. Cause (3) is primarily due to underestimation of the technology advance required. Program uncertainties are directly dependent upon the amount of technical advance to be incorporated into the new system. The ratio of actual total cost to initial estimated total cost varied from 1.0 to as much as 17 depending upon the amount of technical advance required in these aircraft and missile studies (Refs. 5-9).

An analysis of spacecraft costs indicates a similar distribution between the five cost escalation types. A detailed breakdown cannot be obtained in all cases because program records often list only the net cost change for any one year without specific explanation of the cause. In addition to undefined causes of cost escalation, miscellaneous causes which do not directly fit into types 1 through 4 are also included in type 5. These two factors result in an inflated estimate of importance for this cost estimate revision cause.

As an indication of this cost uncertainty, ratios of actual total cost or late-in-program estimates of total cost to initial estimated total cost for various space-related programs are provided in Table 2-1. Sources are primarily Refs. 10 to 17, with some additional information supplied by program managers.

The point in the program at which the initial estimate is taken significantly affects the magnitude of factor numbers. Early estimates tend to be extremely optimistic. These estimates generally are based upon cost estimating relationships which are historically

Table 2-4

PRELIMINARY COST RATIOS

Program	Ratio	Reference
SRAM	3.49	14
Titan 3-C Dev.	1.59	10
Prod.	1.00	10
Pershing I Dev.	1.62	10
Prod.	0.94	10
LOH Dev.	2.25	10
Prod.	0.89	10
XC-142 Dev.	1.79	10
F-111 Dev.	3.93	10
Prod.	1.92	10
Program	2.23	14
C-141 Dev.	1.38	10
Prod.	1.51	10
LANCE Dev.	3.76	14 & 10
SPRINT	1.26	10
Cheyenne	2.86	10
C-5A Dev.	1.14	10
Prod.	1.60	10
Total	1.47	14
Centaur	8.29	16
Scout	4.43	16
Delta	1.97	16
LEM	5.55	16
SIB	2.12	16
SIC	2.30	16
SIVB (SV)	5.49	16
CSM	1.29	16
S II	9.88	16
SIVB (SIB)	1.73	16
Mercury S/C	7.3	16
Gemini	2.71	16
Viking	2.28	14
ERTS A-B	4.35	14
ATS	1.44	16 & 17
Intelsat I-III	2.25	14
GEOS A-B	1.38	14
Nimbus A-D	1.27	14
Tiros – M	1.34	14
Lunar Orbiter	1.72	14
Pioneer A-E	1.97	16 & 17
Surveyor	5.41	14
OAO A-C	2.92	16 & 17
OGO	1.63	16 & 17
OSO A-H	1.90	16 & 17
RAE A-B	2.79	14
Apollo S/C	3.14	16
Ranger	2.29	JPL
Mariner 64-67	2.00	JPL
Mariner 69	1.31	JPL

derived, and may cover less than is later understood to be essential. They generally understate the technological difficulty involved in a given enterprise and the cost of many indirect contributors to total program costs — or even to development costs.

The importance of the time of initial estimate is shown by Fig. 2-1, which is presented in Ref. 12 from unpublished data collected for the Marshall-Meckling study. The curve plots cost factor numbers for a group of fighter aircraft developed in the 1950's against the time at which the initial estimate was made. The horizontal axis is measured in months before Initial Operating Capability (IOC). The zone designated A is roughly representative of time at which a Technical Development Plan for fighter aircraft probably would be approved today. Zone B, somewhat higher on the curve, is probably representative of the period during which a definitive contract emerges or a firm contract target is established. The significant point, of course, is that if observations are taken earlier or later than at A or B, quite different factor numbers will result. As shown by the points on the curve, the observations plotted for programs of the 1950's differ widely in their distance from IOC.

The curve itself, although representative of only one lot of fighter aircraft programs, is strikingly like estimating relationship curves derived by Summers (Ref. 2) for other kinds of aircraft programs and missile developments during the 1950's. Because the object of the survey presented in Ref. 12 was to examine the ability of the Services to predict and control program outcomes in the 1960's in comparison to the 1950's, the bias introduced by taking initial estimates at no definite time in the program was avoided by selecting estimates in Region A whenever available. Region B estimates were used if none were available for Region A. The conclusion reached was that, on the average, estimates in the 1960's were 25% less optimistic than in the 1950's. Thus, Fig. 2-1 should only be used to indicate the relative (not the absolute) change in cost factor as the time of initial estimate changes. The cost factor differential will not be as great for 1960 estimates.

However, the advanced planner who is interested in performing tradeoffs between proposed programs does not have estimates in Regions A or B available for use. He must rely on early estimates available for his analysis. Therefore, whenever possible, these initial estimates were used as the reference for the ratio presented in Table 2-1.

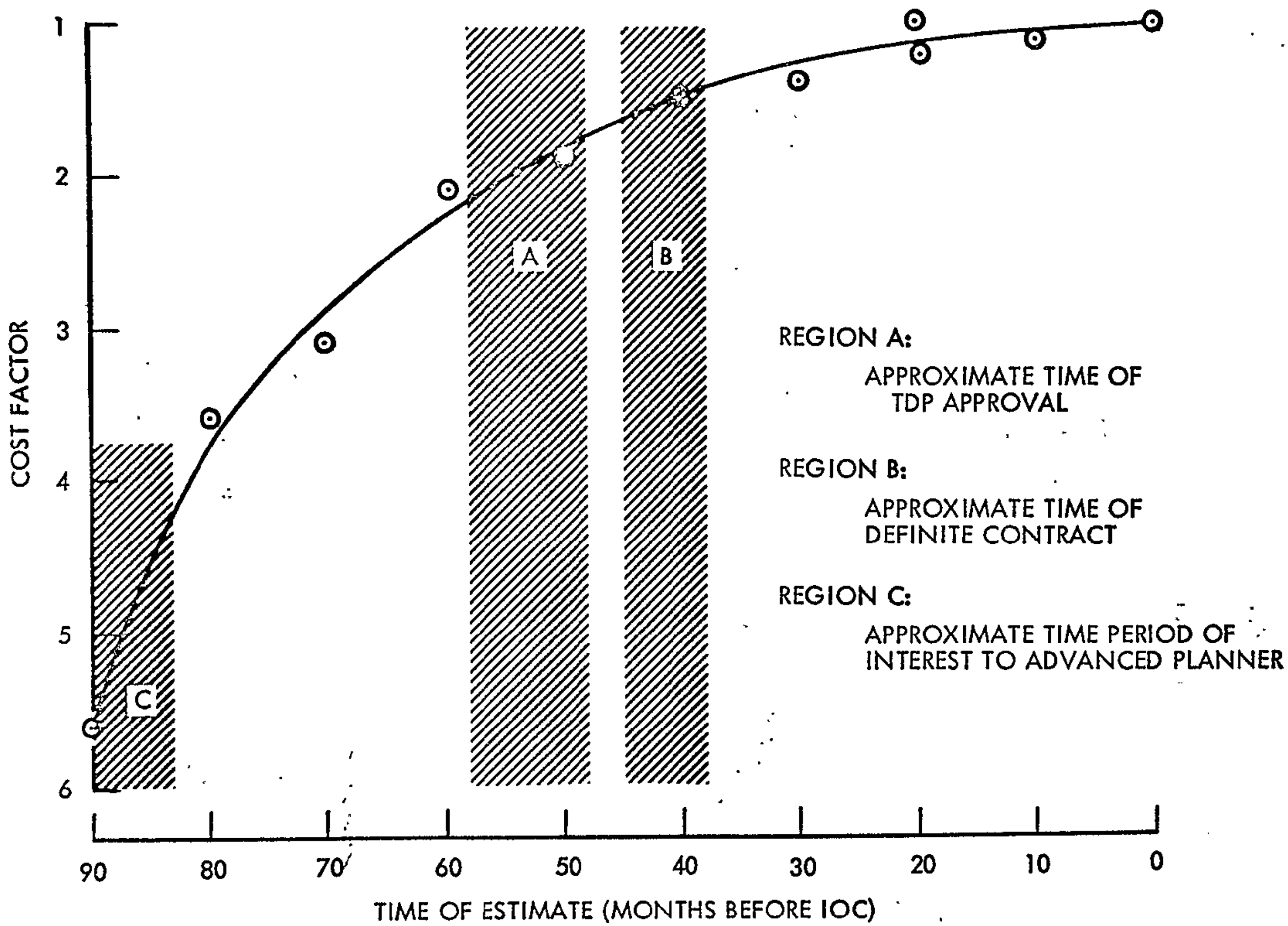


Fig. 2-1 Cost Factors and Time of Initial Estimate

$\left(\text{ratio} = \frac{\text{final cost or last estimate of final cost}}{\text{planning estimate}}\right)$. If a change in program scope occurred between the initial and final estimates, the costs were adjusted accordingly. A statistical analysis based on the ratios presented in Table 2-1 cannot be performed at this time because several of the programs involved were not defined precisely enough at the time of the initial estimate, so that it cannot be determined if adjustments to the data are required or not. More information on these programs is required. Another problem involves the availability of initial estimates. Ratios based on information in Ref. 10 have initial estimates in Region A or B. Estimates in Region C were not available for these programs. Until these biases can be removed, the ratios may only be used as guidelines for the analyst when estimating the uncertainty of available program estimates.

Two characteristics of program costs are evident from the analysis performed to date. Spacecraft programs often have a ratio close to unity. If such a program is in danger of significant overruns, then the number of launches is frequently cut or the program is reduced in scope, resulting in either small total program overruns or actual underruns. Cost adjustments compensate for this characteristic, provided the original program was defined clearly.

Many of the overruns could be accounted for by an increase in final inert weight over that initially proposed. Spacecraft costs tend to increase linearly with weight increases, while launch vehicles or other propulsive systems experience an exponential growth in cost due to increased propellant requirements, weight growth in structure, and other subsystems due to the initial weight growth increment. For example, weight growth of 25:1 is not unusual as a ratio of resulting increase in liftoff weight to an increase in orbiter weight for an earth orbital vehicle.

Launch vehicle programs normally include recurring costs which may vary considerably over long periods of time from that originally planned. Ratios comparing RDT&E costs and recurring costs individually are more informative than just a comparison of total program costs; however, the allocation of funds between RDT&E and the production item is not always clear-cut. When available, the separate ratios are presented.

Some programs are partially funded by other programs. If the degree of sponsorship can be ascertained, the costs were delegated to the appropriate program. Otherwise, (see Mariner 64 and Mariner 67) the program costs were combined before ratios were taken.

Figure 2-2 indicates the shape of the preliminary cost factor distribution taken from Table 2-1. Only cost factors which could be reliably unbiased were used in this figure. Both propulsive and non-propulsive entries were combined in order to smooth the results. However, propulsive and nonpropulsive cost factors have the same general distribution when plotted independently. The main difference is the tail is longer on the propulsive distribution as discussed above.

In conclusion, the cost growth ratios presented in Table 2-1 were based on historical data currently available. More work needs to be done before a complete statistical analysis can be based on them. They may be used as guidelines for the analyst when estimating the uncertainties associated with future program cost estimates.

2.2 COST ESTIMATING UNCERTAINTY

The uncertainty involved in cost estimating errors refers to variations in program costs when program and economic uncertainties are zero, i.e., when the vehicle configuration and all other program and economic parameters are held constant. Reference 5 lists the major sources of cost estimating errors as:

- Cost Estimation Relationship (CER) Errors
- Data Errors
- Extrapolation Errors
- Aggregation Errors

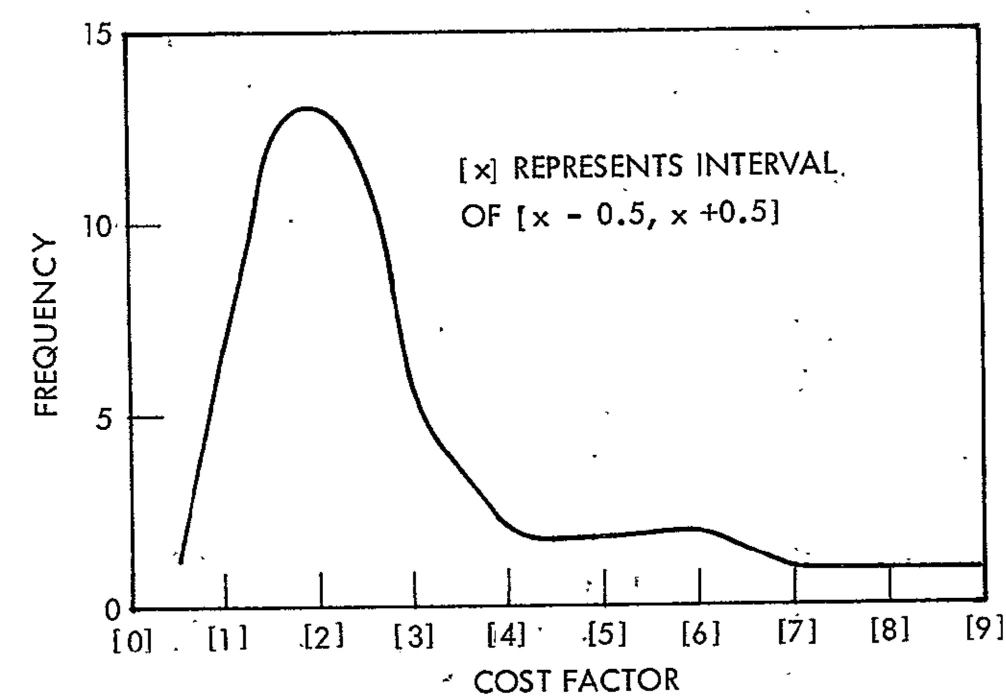


Fig. 2-2 Cost-Factor Distribution

Numerous other sources of uncertainty – such as bias in the analysis, differences in interpretation of hardware requirements, omission of elements in defining an overall program, which for some technology may also be unavailable (i.e., "unknown unknowns," Ref. 18) – are possible for explaining the total variations in cost estimation. However,

the foregoing four error sources constitute a major part of the problem and are discussed below.

CER errors are expected because cost estimating relationships can be assumed to hold only within certain tolerance limits. The cost and engineering data used in deriving CERs invariably contain errors also, due to the complexity and vast quantity of data involved. Extrapolation beyond the range of the samples or data base from which the CER was derived is frequently required since the cost analyst does not have another alternative at his disposal. Extension of the CER into a new region can introduce significant errors. These circumstances indicate some of the potential sources of error in applying CERs to estimate the cost of new systems.

Aggregation errors arise because each analyst sums the cost elements differently. Possibly, the sum of these errors is negligible, due to counterbalancing between individual errors; however, this possibility cannot be assumed in general. Although Refs. 2 to 16 and 19 to 22 provided valuable background material for this study, Refs. 23, 24, and 25 were especially useful because they explore in detail the statistical characteristics associated with cost estimating errors associated with launch vehicle programs. The conclusions in general are as follows:

- Sample standard deviations range from 31 to 90% of corresponding mean value.
- Nature of each sample distribution indicated it was unimodal and either nearly symmetric or skewed positively. Total program cost was unimodal and either symmetric or skewed positively. (Reference 25 indicates that RDT & E cost uncertainties tend to be positively skewed while investment and operations cost uncertainty are more likely to be symmetric in their distribution.)
- Since existing technology was assumed in order to minimize program uncertainties, RDT&E program costs were relatively certain. Under these circumstances, operational program costs showed the greatest variation due to large discrepancies in estimating unit flight hardware cost. In advanced technology programs, RDT&E costs will also have significant cost uncertainty.

- Category 1 uncertainties are as large as the program (or Category 2) uncertainties discussed in section 2.1. If an extensive development program had been postulated for this analysis, the variation of the RDT&E estimates would have been much larger and further increased the variation in total program costs.
- Although lower-level cost uncertainties are skewed, their independent sum quickly converges to the normal distribution. Thus, the observed skewness of the aggregate program cost uncertainty has to be due to one or more of the following possibilities:

  (1) One cost element dominates all others in magnitude.

  (2) Program elements are correlated.

  (3) Uncertainties (other than cost estimating uncertainties) such as engineering change, schedule change, and system performance change uncertainties are important.

2.3 PROGRAM SCHEDULE COST RELATIONSHIPS

Accelerated and stretched-out development programs result in increased expected costs over the nominal program development time. The relationship between time changes in the development program period and increased costs was determined for a typical program having an 8 year nominal development period and involving both a spacecraft and launch vehicle development. Refs. 2, 16 (1965 in particular), 26, 27, and 28 were principal sources for this analysis.

The determination of the relationship between development costs and phasing of development begins with the cost analysis illustrated on Fig. 2-3. The direct costs consist of manpower and material. Manpower can be broadly separated into manufacturing labor and engineering labor. Material consists of purchased raw material/supplies, minor subcontract items, and major subcontractor costs. The indirect costs are those required to support directly the engineering, manufacturing, planning, and material-processing efforts, and the overhead and general administrative costs which are required for maintaining the physical plant and providing administrative supervision, clerical support, and related effort.

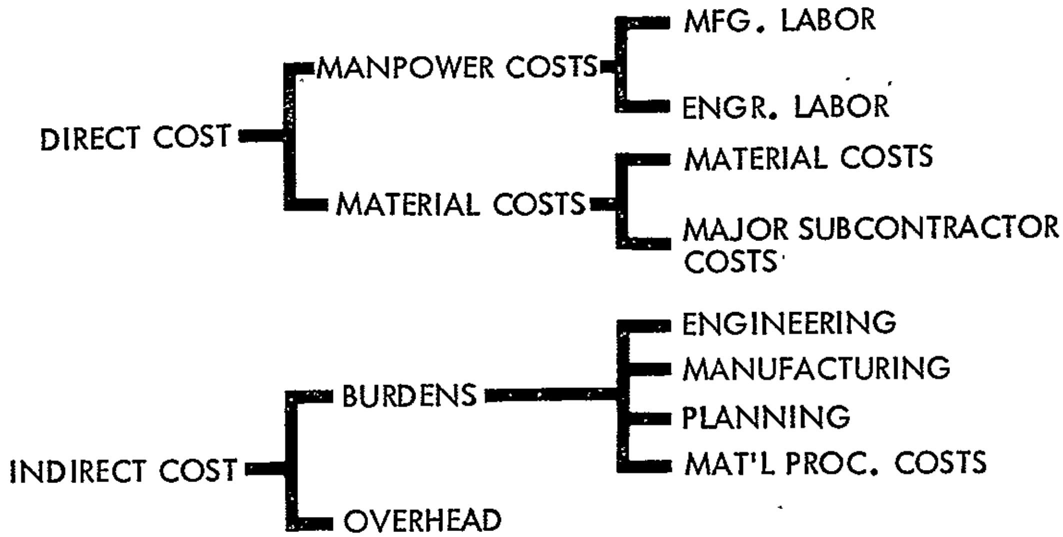


Fig. 2-3 Cost Analysis

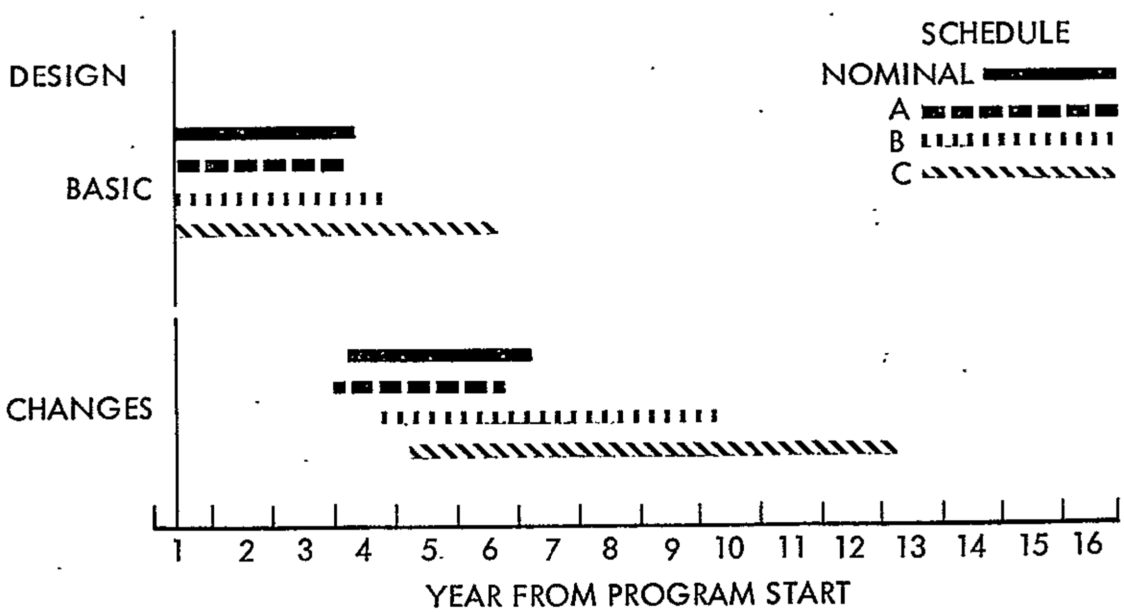


Fig. 2-4 Spacecraft Program Phasing – Design

The groundrules for this analysis, which has been extracted from NASA reports, include:

- Nominal development plan and program elements are the base for the study.
- Delayed schedules are to assume a stretchout of nominal program elements without major revision to the definition of these elements.
- The schedules analyzed include:
  - N – nominal schedule
  - A – 6% acceleration
  - B – 37.5% delay
  - C – 75% delay

Figures 2-4 through 2-6 illustrate how the spacecraft program phasing varies with schedule. These charts divide the total project activity into periods of design, manufacturing, and test and compare the four different schedules above in terms of period of time occupied in each of these activities. Such phasing analyses are essential in arriving at costs associated with each category of effort. Figure 2-4 divides the schedule for spacecraft design into two parts, that for basic design of the components and that of the engineering support required to carry on the design changes for each of the schedules. As a complicated research and development program develops, many design changes become necessary as development data feed back from ground and flight tests. As the flight program is stretched out, then the design period must also be stretched. For the longest stretchout considered, the design period for incorporating changes would actually stretch out to be almost three times as long as for the nominal schedule. Therefore, a minimum staff of design engineers must be maintained to accommodate these changes for that period of time. Since the design work requires many different disciplines, a minimum level of capability is needed in each of these different areas. Thus a minimum engineering staff is required for the ability to respond to all of the changes that may be necessary as the flight program proceeds. The size of this staff is relatively independent of the number of launches attempted each year. If this staff is not fully utilized because the program was stretched, then money is being spent ineffectively.

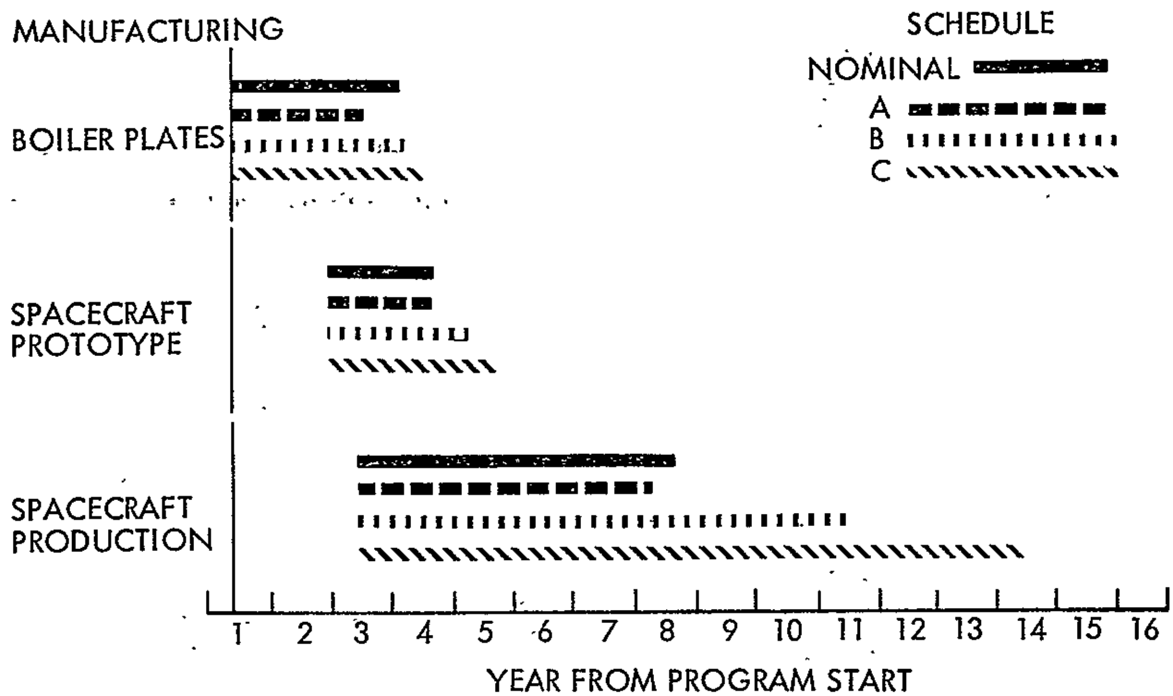


Fig. 2-5 Spacecraft Program Phasing – Manufacturing

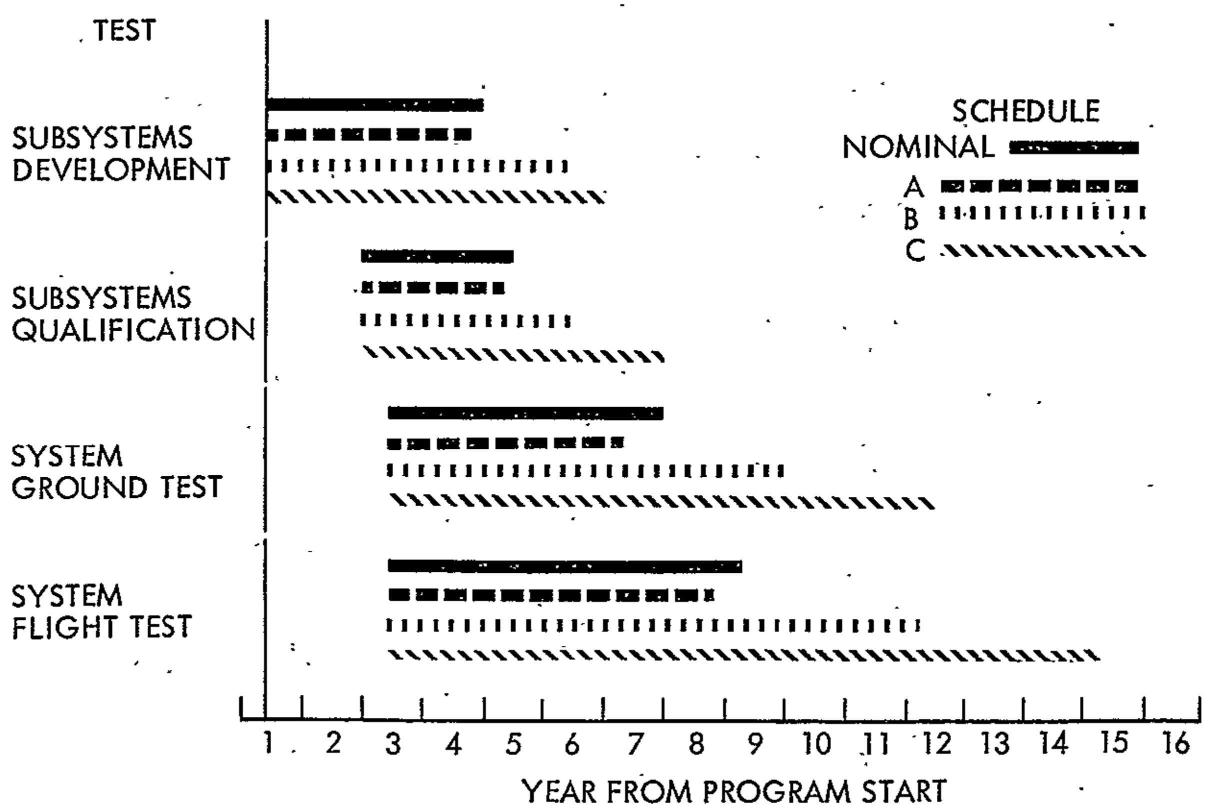


Fig. 2-6 Spacecraft Program Phasing – Test

In manufacturing, boiler plates, prototype spacecraft, and production or operational spacecraft must be built. The spacecraft prototype may be delayed somewhat, but delay beyond a certain point results in large increases in spending because the prototype fails to serve its intended purpose.

The main stretchout in activity would be in the fabrication of production spacecraft. The direct production effort is more suitable for efficient stretchout than is the direct engineering effort. The direct manhours required for manufacture of production spacecraft are close to constant regardless of the schedule (Ref. 26). Overhead increases significantly, however, for the stretched out manufacturing period.

There are four major phases in the test activity: (1) subsystems development, (2) subsystems qualification, (3) systems ground tests, and (4) systems flight tests. Phases (1) and (2) are stretched out in accordance with the first flight date to which these phases are tied. Phases (3) and (4) have significant stretchouts for the different flight schedules under consideration.

In estimating the prime contractor costs, a step-by-step analysis of the manhour requirements for engineering and manufacturing tasks that must be performed is first made. Then the subcontractor items are similarly analyzed with assistance from major subcontractors involved.

Once the direct costs have been estimated, the management and overhead costs required to support the direct effort are added. The amount of overhead does not decrease in proportion to a decrease in direct labor. Keeping a facility open and running costs some minimum amount, whether any directed effort is applied or not. The overhead charged also varies with the total amount of company business at a given time.

The relative overall cost estimates for each major component's development under the four schedules considered are presented in Figs. 2-7 through 2-9.

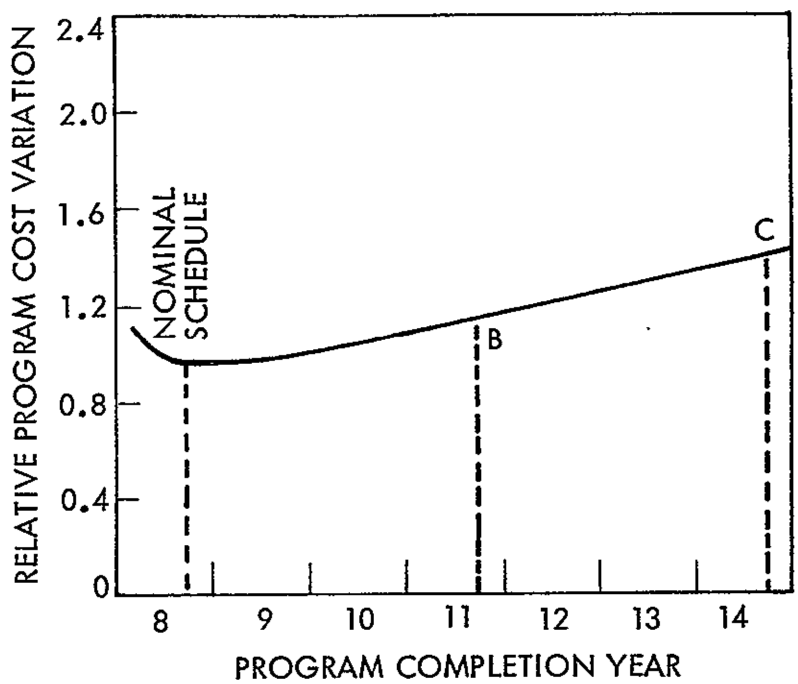


Fig. 2-7 Spacecraft Cost Variation

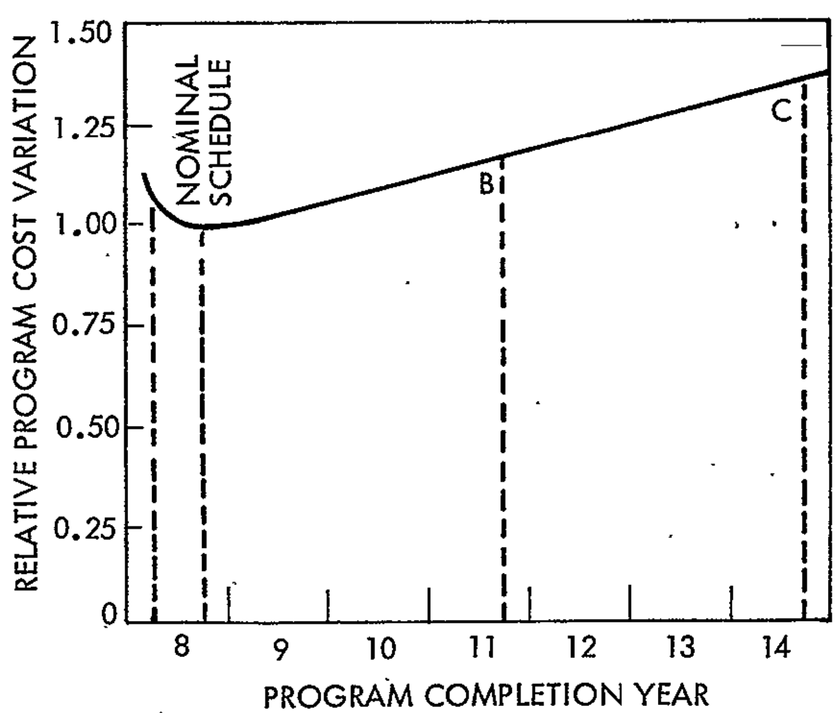


Fig. 2-8 Launch Vehicle Cost Variation

These schedules are combined and analyzed to produce an overall program cost for each component and then for the total program. Since there is more than one way to combine component schedules in order to arrive at total program cost for a fixed completion date, there is a range of total costs which can be expected. A reasonable range is indicated on Fig. 2-10. Figure 2-11 summarizes total costs for the optimal combination of components for each program completion time considered. The 6% accelerated program results in at least a 6% increase in total cost. The 37.5% delayed program increases costs 15% while the 75% delay causes a 35% increase in total program cost. An analysis of how the cost varies by year within the program

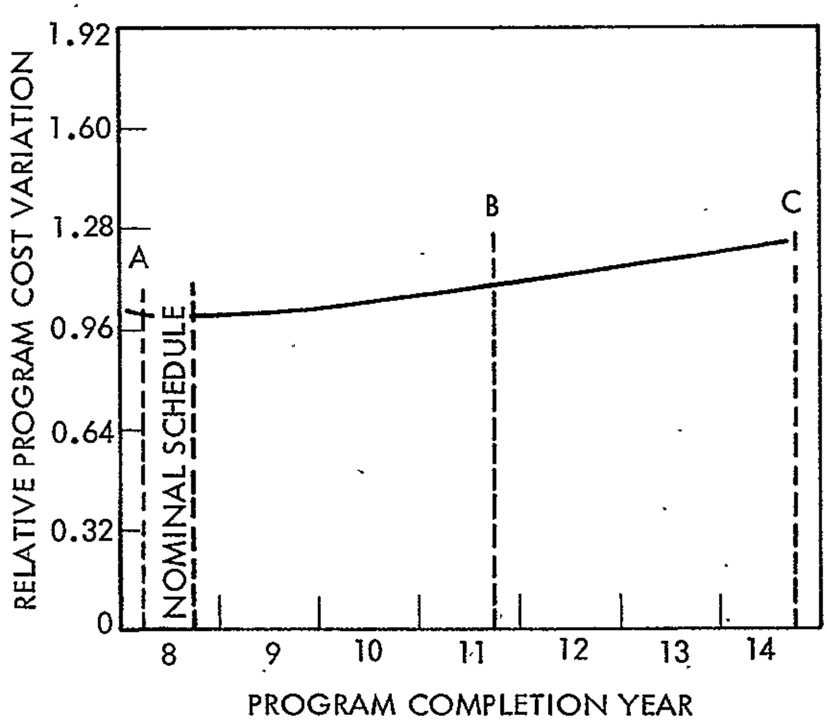


Fig. 2-9 Engine R&D Cost Variation

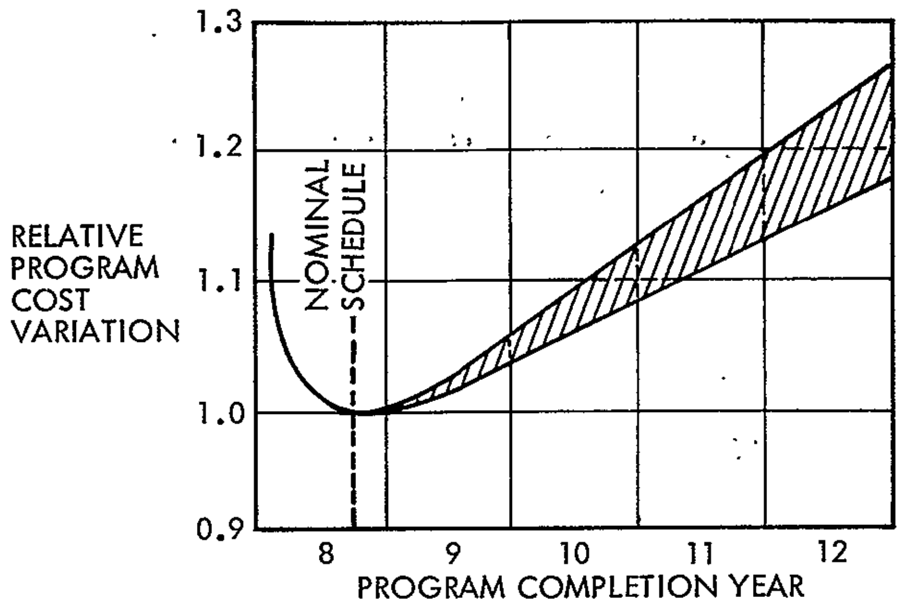


Fig. 2-10 Total Program Cost Variation

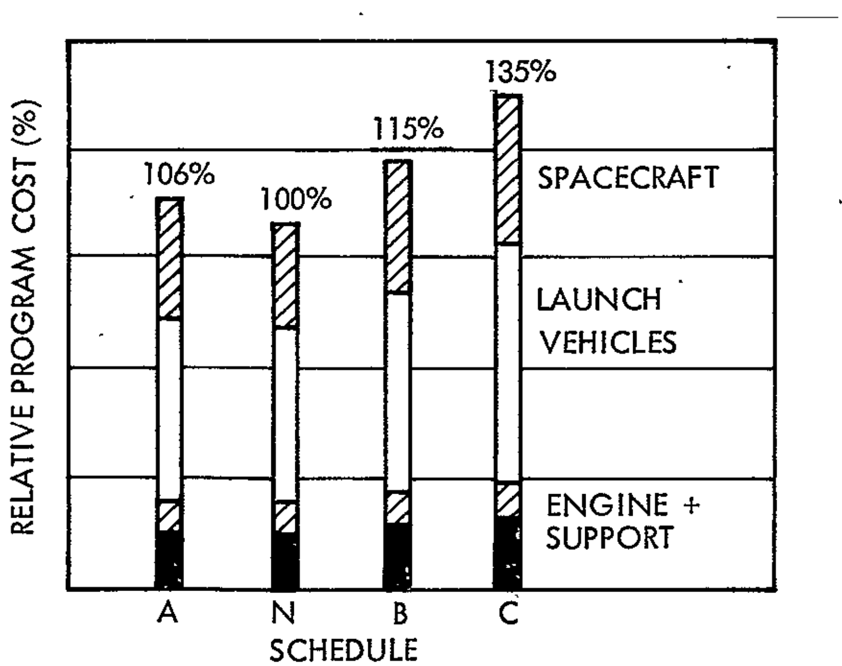


Fig. 2-11 Program R&D Cost Summary

shows that a delayed program does result in some cost reduction for certain years. However, the sum over all the years is greater than the nominal case. Since the computer model developed distinguishes between launch vehicle development programs and spacecraft development, Figs. 2-7 and 2-8 are of special interest.

The preceding analysis indicates that certain fixed operating, personnel, and facilities costs account primarily for the increase in total costs of a decelerated (stretched) program. For example, a significant number of skilled engineers, scientists, and technicians are needed to support the flight and ground-test activity that is required throughout the development program. These personnel include propulsion, electronics, structures, thermodynamics, astrodynamics, and guidance and control specialists, as well as supporting technicians, plus the clerical and management staffs required by each industrial contractor to support the effort.

All these costs remain practically the same on a time basis regardless of program pace or launch rate. Because these costs accumulate in almost direct proportion to the time required for program completion, a stretchout would substantially increase them. It would also reduce useful output and require maintenance of a technical-industrial base in low-gear operation over a longer period of time.

An accelerated program, on the other hand, reduces these fixed costs since development time is shortened. However, parallel efforts are often conducted in this situation on essential subsystems/components that have high technical risk to increase the probability of satisfactory completion within the shortened period of time. These parallel efforts increase costs substantially. Even if cost were not a limiting factor, no more than a 30% acceleration is allowed in general due to technological limitations (Refs. 26 and 27). These relationships and limitations are part of the smoothing portion of the existing model.

2.4 CONCLUSIONS

As a result of this preliminary survey of historical data, the following conclusions are apparent:

(1) Cost estimates of important parameters made early in a program are usually quite inaccurate in two respects. First, these estimates are strongly "biased" toward overoptimism. Second, aside from bias, errors in estimates evidence a substantial variation.

(2) The accuracy of estimates is a function of the stage of development; i.e., estimates improve as development of the item progresses. Similarly, estimates for development projects representing only "modest advances" tend to be better than for more ambitious projects. Further, the actual length in time of a development program directly influences the variation in cost estimate.

(3) Cost estimating uncertainties behave statistically as though they were distributed on a unimodal curve which is either symmetric or (most often) skewed left. The parameters associated with this curve depend on the type of program being estimated and exhibit characteristics as described in section 2.2.

(4) Mission (payload) related cost uncertainties have the same general characteristics as launch vehicle costs; however, the magnitude of expected mission costs is greater while the uncertainty is less than for general launch vehicle costs.

(5) Even though independent sums of skewed distributions quickly converge to the normal distribution, the mean (and mode) of the approximating normal distribution is not the sum of the modes of the component distributions. Thus merely summing the most likely costs of component programs does not give a valid indication of the cost of the total program.

(6) As program development time is increased (development stretch), costs increase mainly due to certain fixed costs being spent over a longer period of time. As program development time decreases (development acceleration), parallel efforts often take place, causing an exponential increase in total costs.

Section 3

ANALYTICAL APPROACH

The development of a model which compares risks between different programs and estimates the probability of program costs exceeding cost estimates must be based upon historical data. This section compares various statistical distributions in terms of their ability to meet the requirements determined in Section 2. The log-normal distribution is selected as most useful. The characteristics of this distribution are provided as well as a description of the analytic relationships incorporated into the model which transform the model from a deterministic to a statistical evaluation tool.

3.1 DATA DISTRIBUTIONS

The statistical analysis of cost data presented in Section 2 has indicated the type of distribution which best describes the anticipated cost uncertainties. Figure 3-1 indicates the general shape to be expected.

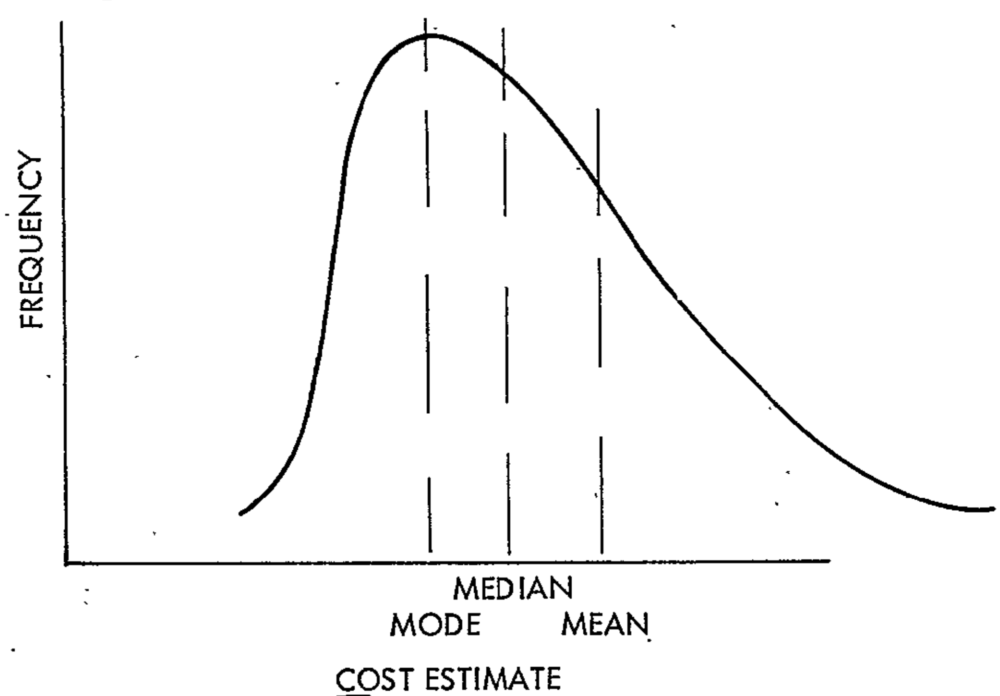


Fig. 3-1 Distribution of Cost Estimate

There are three general distributions which have the characteristics shown in Fig. 3-1: (1) the log-normal (Λ) distribution, (2) the gamma (Γ) distribution and (3) the beta (β) distribution. The Γ distribution has the real axis from 0 to infinity as its domain and for some values of the parameters looks like the distribution in Fig. 3-1. The χ^2 distribution (a special case of the Γ distribution) has the added property that the sum of any number of χ^2 distributed variables is again χ^2 distributed. There is one major disadvantage to the use of this distribution, however. Although the Γ distribution has two parameters, one parameter is only used for "sizing" and, hence, many shapes anticipated for actual error distributions cannot be approximated accurately.

The β distribution (and the triangular distribution sometimes used to approximate the beta) is a "real" two-parameter function allowing close approximation to all the anticipated distributions including the symmetric ones. Both positive and negative skewing may be approximated. The main disadvantage of this distribution is that the unit interval is its domain and thus normalization is required. Since there is a positive probability that costs may exceed any given number, normalization is an arbitrary procedure limiting the usefulness of this distribution.

The log-normal distribution has the advantage of being both a "real" two-parameter function, and a function whose domain is the positive real axis. Thus, close approximations are available for all positively skewed and symmetric distributions. Since there is a positive probability of reaching any positive real number, normalization is not necessary. The sum of many variables, each distributed log normally, is not necessarily distributed as another log normal function. However, historical data indicate that the total cost should also be distributed as in Fig. 3-1. Therefore, key parameters describing the sum are used to approximate the sum as another log normal variable.

Other distributions, similar to the three discussed above, were found unsuitable for the analysis for some of the same reasons given above.

Because the log-normal distribution is easy to work with and has the essential characteristics dictated by historical data, it was chosen as being most representative of the expected cost-error distributions.

3.2 CHARACTERISTICS OF THE LOG-NORMAL DISTRIBUTION

While the exponential distribution makes use of the arithmetic mean of the variable, the log-normal distribution makes use of the geometric mean of the variable, or the arithmetic mean of the logarithm of the variable. Since the log-normal distribution is basically a two-parameter distribution, it cannot be specified by the mean alone.

The log-normal distribution is skewed, but approaches the normal as the standard deviation of the associated normal distribution approaches zero. It has been characterized by some as a model of the law of proportionate effect and has been shown to be applicable to many economic, biologic, and advanced technologic processes (Refs. 29 and 30).

A random variable is said to have a logarithmic normal (log-normal) distribution if the logarithm of the variable is distributed normally. If x is a positive variate $(0 < x < \infty)$ and if $y = \ln x$ is normally distributed with mean μ and variance σ^2, then x is said to be lognormally distributed. The distribution function may be written as

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}} \tag{3.1}$$

where

$$\mu = \overline{\ln x}$$
$$\sigma^2 = \text{var } (\ln x)$$

The following relations hold:

$$\begin{aligned} \text{median of } f(x) &= e^{\mu} \\ \text{mean of } f(x) &= e^{\mu+0.5\,\sigma^2} \\ \text{mean of } f(x) &= e^{\mu-\sigma^2} \end{aligned} \tag{3.2}$$

Thus, one can calculate values for f(x) using standardized normal tables for f(y = ln x).

3.3 INTERNAL PROGRAM MODIFICATIONS

Input is provided basically by two costs for each item instead of the single cost used in the deterministic model. The most likely cost, m, is estimated first, based on the most realistic estimate available. Next a pessimistic cost, b, is estimated such that the probability of exceeding this cost is x% where x is less than 50. The choice of m and b will determine how skewed the distribution will be. The nature of the item must be taken into consideration when estimating m and b as discussed in Section 2. Maximum cost estimates should include the possibility of initial failure and a new start in one or more components of a program or of program redefinition.

Using the relationships (3.2) presented in Section 3.2, the input data are developed as follows:

For each cost, two values are input:

$$\begin{aligned} m &= \text{mode} = e^{\mu-\sigma^2} \\ xx &= x\% \text{ tail such that prob } (Y \geq xx) = x/100 \end{aligned} \qquad (3.3)$$

Y is defined by $N(Y \mid 0, 1) = 1 - x/100$, N being the normal cumulative distribution, so we have

$$\begin{aligned} \sigma \text{ (parameter)} &= \frac{-Y + \left[Y^2 + 4 \ln\left(\frac{xx}{m}\right)\right]^{1/2}}{2} \\ E \text{ (mean)} &= m\, e^{3/2\, \sigma^2} \end{aligned} \qquad (3.4)$$

and

$$\beta \text{ (variance)} = E^2 (e^{\sigma^2} - 1)$$

E and σ are stored for each cost since all other variates are functions of these two. The algorithm proceeds as before to find a solution based now on expected values for all component costs. Once this solution is found, the appropriate statistical parameters are used to determine the distribution characteristics associated with the total program cost for this solution. The individual expected values are simply added to determine the total program expected cost [Eq. (3.6)]. The variance is found assuming either complete independence or complete dependence between variables depending upon the situation, [Eq. (3.7)]. For example, recurring costs for stage X in year Y are assumed to be completely dependent on these same costs for year Y + 1. The algorithm continues to find solutions, whose total expected costs are placed in ascending order, until n solutions have been found where n = NSOL is an input variable. As each solution is found, the corresponding assignment is printed out along with information concerning its total cost distribution and its relation to other solutions found previously.

If inflation at an average rate p = GRO is input, then the relationship used is

$$m' \text{ (in year } Y + N) = (1 + p)^N \, m \text{ (in year } Y)$$

$$\text{var}' \text{ (in year } Y + N) = (1 + p)^{2N} \, \text{var (in year } Y)$$

Parameters for the total program cost are calculated using Eqs. (3.6) and (3.7).

$$E \text{ (total cost)} = \sum_i \left[k_{1_i} + k_{2_i} (1 + p) + k_{3_i} (1 + p)^2 + \ldots + k_{N_i} (1 + p)^{N-1} \right] E_i \tag{3.6}$$

$$\text{var (total cost)} = \sum_i \left[k_{1_i} + k_{2_i} (1 + p) + k_{3_i} (1 + p)^2 + \ldots + k_{N_i} (1 + p)^{N-1} \right]^2 E_i^2 \left(e^{\sigma_i^2} - 1\right) \qquad (3.7)$$

where

k_{j_i} = number of times cost i is used in year j, $1 \le j \le N$

The effect of dependence (correlation) on uncertainties associated with input data may be displayed graphically as in Fig. 3-2. For each variable associated with one program element (the two chosen here are the development cost and the operating cost of one reusable vehicle), the parameters μ and σ are calculated for the associated normal distribution. Then

$$G = \frac{1}{(1 - \rho^2)} \left[\frac{\left(x - \bar{\mu}_x\right)^2}{\sigma_x^2} - \frac{2\rho\, (x - \bar{\mu}_x)\, (y - \bar{\mu}_y)}{\sigma_x\, \sigma_y} + \frac{\left(y - \bar{\mu}_y\right)^2}{\sigma_y^2} \right]^2 \qquad (3.8)$$

determines the probability ellipse in the normal plane.

If we assume that $\sigma_x = \sigma_y$ (i.e., the two variables have the same growth factor), then the major axis = $\sigma \left[G (1 + \rho)\right]^{1/2}$ and the minor axis = $\sigma \left[G (1 - \rho)\right]^{1/2}$ with the center at $(\bar{x}, \bar{y})$. This ellipse in the normal plane is then mapped back into the log-normal plane, yielding results similar to those shown in Fig. 3-2. For a 50% probability ellipse $G = (1.177)^2$. Since the area of an ellipse is πab, Table 3-1 shows, under the above assumptions, how the area of a fixed probability ellipse decreases as the amount of correlation increases.

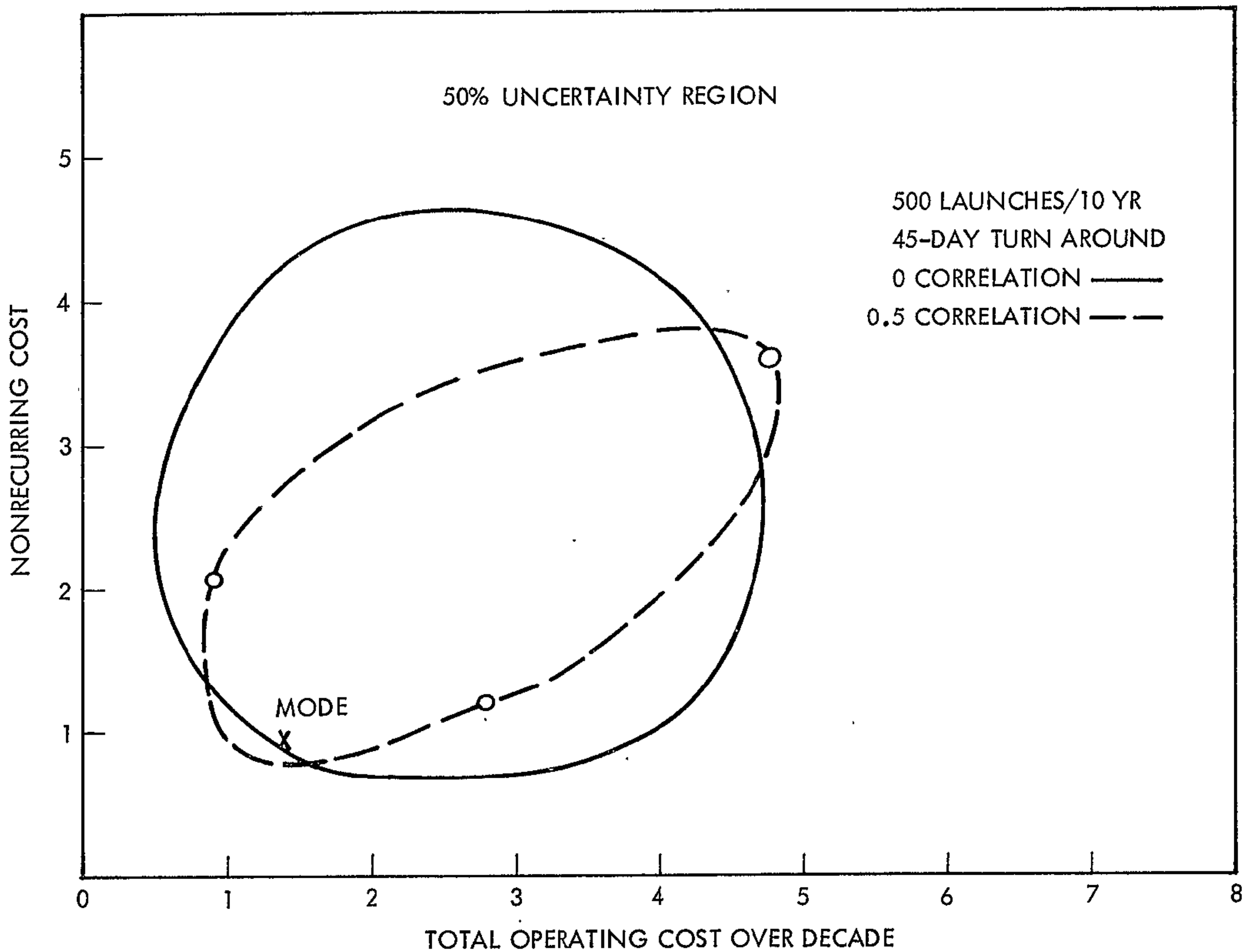


Fig. 3-2 Uncertainty Region for Input Data

Table 3-1

AREA OF PROBABILITY ELLIPSE

Correlation (ρ)	Major Axis (a)	Minor Axis (b)	Area
0	1.177σ	1.177σ	$\pi\sigma^2 G$
0.1	1.295σ	1.06σ	$0.995\ \pi\sigma^2 G$
0.25	1.463σ	0.884σ	$0.965\ \pi\sigma^2 G$
0.4	1.65σ	0.707σ	$0.9165\ \pi\sigma^2 G$
0.5	1.77σ	0.59σ	$0.866\ \pi\sigma^2 G$
0.6	1.89σ	0.472σ	$0.80\ \pi\sigma^2 G$
0.9	2.24σ	0.117σ	$0.436\ \pi\sigma^2 G$
1.0	2.34σ	0	0

Because the areas described in Table 3-1 have complex shapes in the log-normal plane, more sophisticated equipment than the impact printer is required to produce them. Since the computer program is to be as versatile as possible, in the present work the above results are not produced directly but may be derived from the data output. In the more complete case, with three basic cost categories input, the uncertainty region for a given probability will be a volume having log-normal characteristics. A CRT display, which has better capability for presenting three dimensional data, would provide quicker reaction and more lucid output results.

In the present model subroutine SMOTHS plots total costs on a yearly basis with their corresponding statistical parameters. Payload costs are treated in the same manner as launch vehicle costs. If a development program is stretched or accelerated in this subroutine, the expected development cost will increase, as explained in Section 2. Based on historical data, the uncertainty associated with a stretched program will also increase. However, although introduction of parallel development approaches in some of the component developments of an accelerated program will increase the expected cost of the development, a reduction in the dispersion or risk of the outcome

and possibly a reduction in the uncertainty associated with the new expected cost may result (Ref. 16). Thus new expected costs and uncertainties are calculated in SMOTHS whenever a program development period is changed.

3.4 OUTPUT

The analyst will be attempting to select a fleet of launch vehicles and associated program elements to accomplish a proposed set of missions from alternative combinations. He will want to determine the margin of cost difference between alternative choices. A wide variety of output is available from the algorithm since, for each solution, the log-normal distribution with its associated parameters is known. Equations (3.6) and (3.7) define the expected value and the variance of each total program cost. The parameters, σ, μ, for each such assignment may then be found using

$$\frac{\text{var (TC)}}{[\text{E (TC)}]^2} = e^{\sigma^2} - 1 \tag{3.9}$$

and

$$\mu = \ln [\text{E (TC)}] - \frac{\sigma^2}{2} .$$

The most likely value, m , for each assignment is determined by

$$m = \text{mode} = \text{E (TC)} \left(e^{-3/2\sigma^2}\right) \tag{3.10}$$

The probability that the total cost will not exceed some value Y may be found from the following relationships:

$$\text{prob } (X \leq Y) = p \text{ which is equivalent to } N(Z \mid 0, 1) = p \tag{3.11}$$

where

$$Y = e^{(\sigma Z + \mu)}$$

The scientific subroutines NDTRI and NDTR can be used to find Z given p or p given Y, respectively. Using the above relationships, the probability that the expected program value (mean) will exceed the estimated value (mode) is determined.

To compare two assignments, the probability that one assignment will actually cost more than the other should be known. The log-normal distribution allows such a determination providing that the degree of correlation between programs is provided.

Thus, two assignments involving different development programs may be highly correlated if each development program involves the same type of risk, or they may be only slightly correlated if one involves a large new development and the other utilizes existing technology to accomplish the same mission profile.

Two assignments with total costs C_A and C_B distributed log-normally will have parameters $[V(TC_A), E(TC_A)]$ and $[V(TC_B), E(TC_B)]$ determined by Eqs. (3.6) and (3.7). The parameters (μ_A, σ_A) and (μ_B, σ_B) may be determined by Eq. (3.9). Then $\log C_B/C_A = \log C_B - \log C_A$ is normally distributed with mean $= \mu_B - \mu_A$ and variance $= \sigma_A^2 + \sigma_B^2 - 2\rho\, \sigma_A\, \sigma_B$ where ρ is the correlation coefficient, discussed above, which describes the relationship between assignments C_A and C_B.

Thus the probability that assignment B will cost less than assignment A is

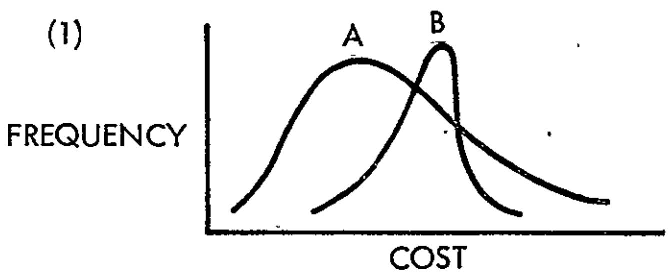
$$\Pr\left(\frac{C_B}{C_A} < 1 \,\middle|\, \frac{\mu_B}{\mu_A} = k \text{ and } \rho \text{ given}\right) = \Pr\left(\ln \frac{C_B}{C_A} < 0\right) = N\left(0 \,\middle|\, \mu_B - \mu_A = \text{mean} \right.$$

$$\left. \text{and } \sigma_A^2 + \sigma_B^2 - 2\rho\, \sigma_A\, \sigma_B = \text{variance}\right)$$

$$= N\left[\frac{\mu_A - \mu_B}{\left(\sigma_A^2 + \sigma_B^2 - 2\rho\, \sigma_A\, \sigma_B\right)^{1/2}} \,\middle|\, 0, 1\right] \quad \text{for } \rho < 1 \tag{3.12}$$

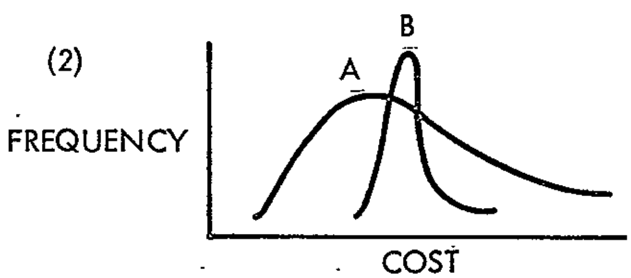
The probability expressed in Eq. (3.12) is output for representative values of ρ for all pairs of assignments of interest so the analyst may obtain insight into the interrelationships between the assignments. Possible comparisons include the following two examples:

(1)



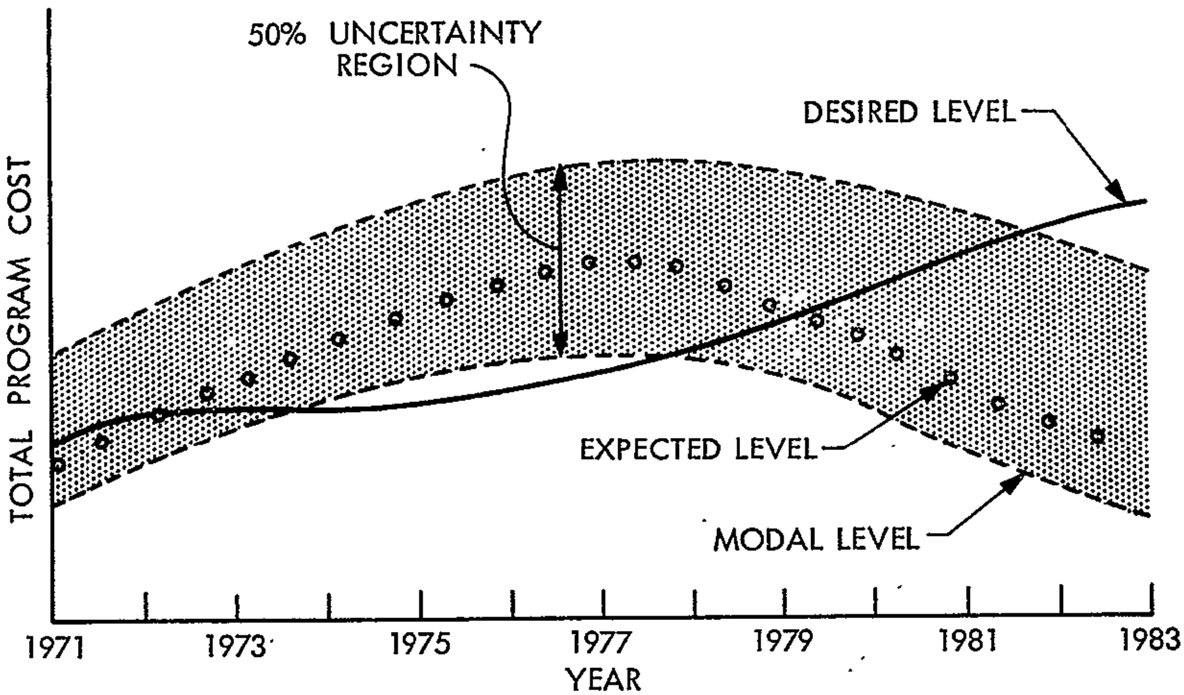
E (B) > E (A) but Prob (A > B) is large. Choice depends on outside factors. (A and B represent alternative total program assignments.)

(2)

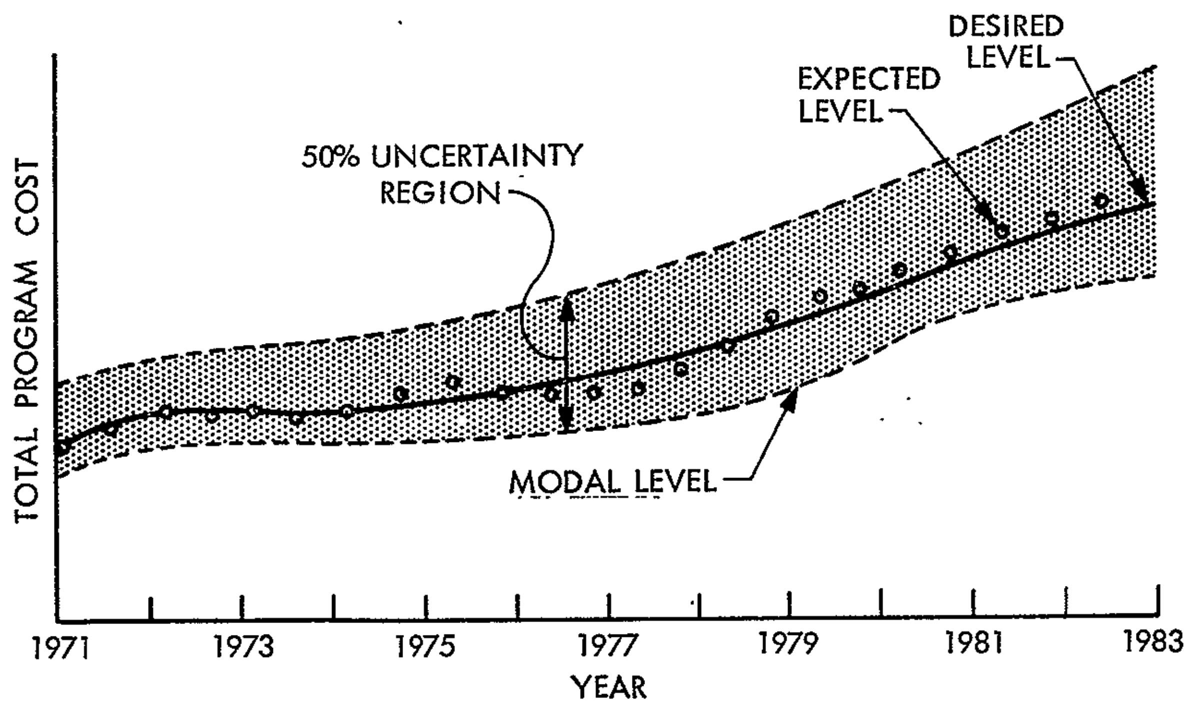


MODE (B) > MODE (A) so deterministic analysis would choose assignment A; but E (B) < E (A). Therefore, using estimated costs (MODE) alone results in invalid conclusion. Statistical presentation shows complex relationships so that valid conclusions can be determined.

The optimal assignment is displayed in SMOTHS with the results printed year by year. The graphical display includes the 50 percent confidence limits for each year (Fig. 3-3). Additional data on output modes are provided in Section 4.5 and Appendix B (Vol. 2).



(a) 50% CONFIDENCE INTERVAL BEFORE SMOOTHING



(b) 50% CONFIDENCE INTERVAL AFTER SMOOTHING

Fig. 3-3 Typical Output Plots

Section 4
COMPUTER MODEL DESCRIPTION AND OPERATION

This section describes the probabilistic optimal assignment and budget smoothing model developed during this phase of work. The logic for the model is described in this section and is detailed in Appendix C (Vol. 2). A summary description of variables which may be input to the program is included in Table 4-1 (presented in Section 4.2). Appendix A (Vol. 2) lists the input requirements in detail along with a glossary of input terms. A sample case illustrating the type of probabilistic input and output which may be generated by this model is included in Appendix B (Vol. 2). The sample case may also be used for program checkout. This section indicates the flexibility of the model available through its many options. Also included are examples of sensitivity tradeoffs that can be derived from output runs using the model, and the application of the model to advanced technology systems.

4.1 LOGIC

The optimum assignment program is integrated with the budget smoothing program through use of a master program which translates from one model to the other. The deterministic budget smoothing program was developed by R. E. Slye, the Technical Monitor for the study, and has been described in Ref. 1. This smoothing program was extended to handle probabilistic input and to output budget levels showing inherent cost uncertainties. It is therefore further discussed in this volume. A general logic diagram of the master program and the two main subroutines, ASIGNS and SMOTHS, are presented in Figs. 4-1 through 4-3.

The master program (MASTER) calls first the vehicle assignment program (ASIGNS) in order to obtain mission data, cost data, and optimum vehicle-to-mission assignment based on these data. Input data are output using both modal and expected values if

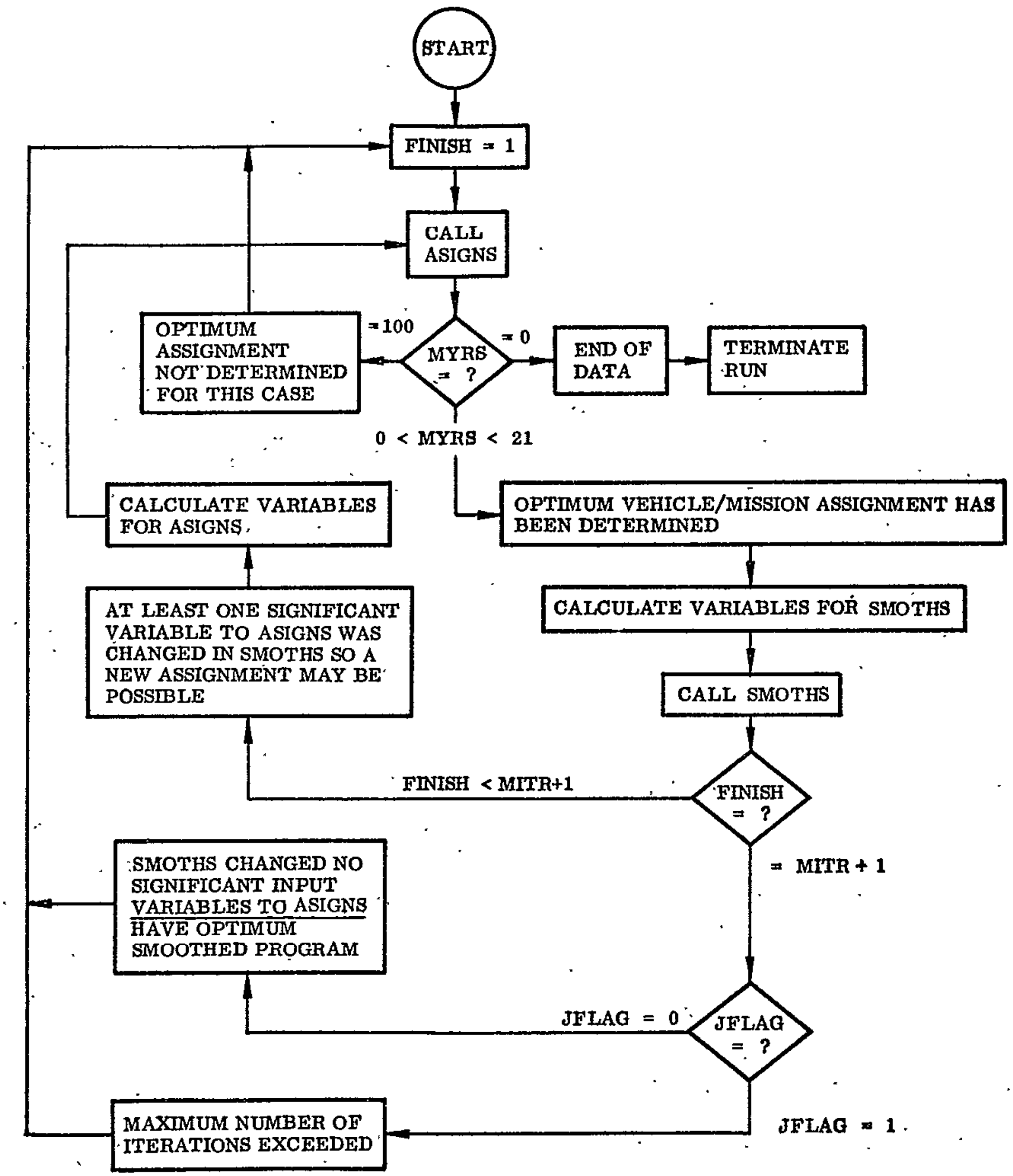


Fig. 4-1 General Flow Diagram for MASTER Program

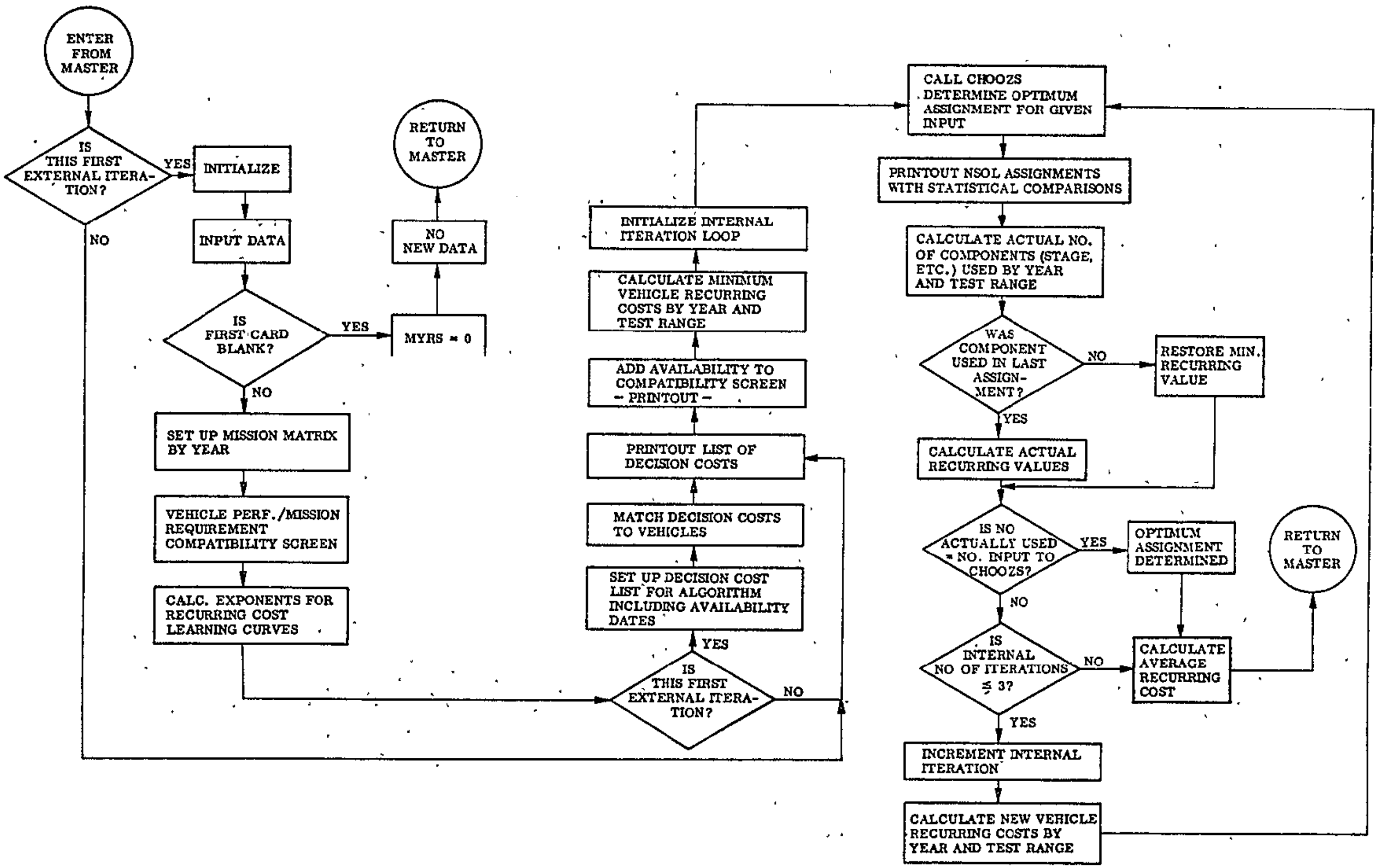


Fig. 4-2 General Flow Diagram for ASIGNS Program

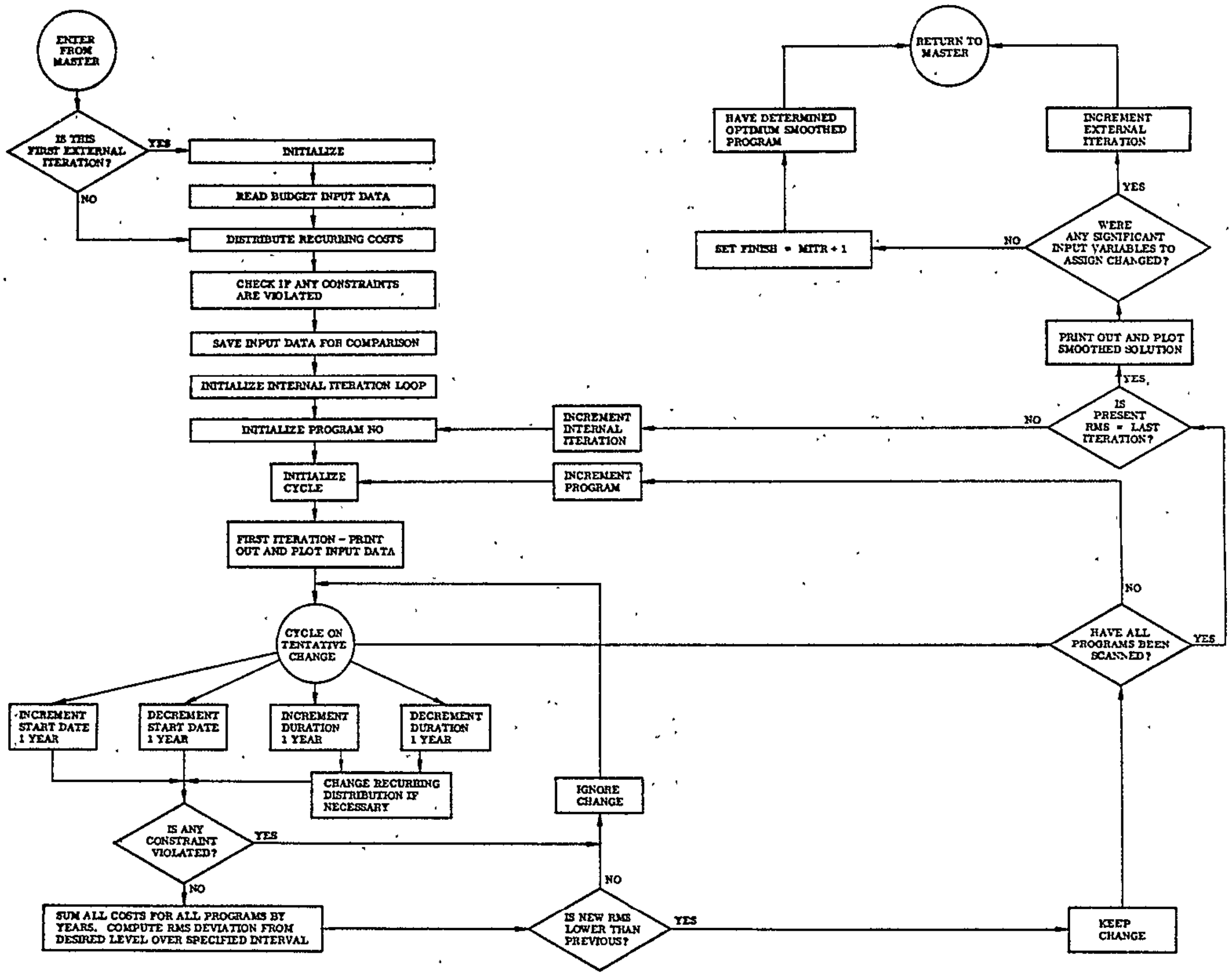


Fig. 4-3 General Flow Diagram for SMOTHS Program

appropriate. The N best solutions based on expected costs are output along with their statistical relationships, but only the optimal assignment is saved for use by MASTER. MASTER then transforms this data from the optimal assignment so that it may be used directly by the budget smoothing program (SMOTHS). SMOTHS shifts development dates, launch dates and development duration to achieve a level of spending close to the desired level. The desired levels of spending and constraints on possible program shifts are input to SMOTHS directly. Annual spending levels are output by SMOTHS based on expected costs and most likely costs. A 50% confidence interval about the expected cost is output and displayed on each plot of annual spending levels.

The new development dates and development costs generated by SMOTHS are transformed by MASTER so that ASIGNS can use the data for a revised vehicle to mission assignment. The program iterates between ASIGNS and SMOTHS until no major changes are generated by SMOTHS. Then MASTER either terminates or starts a new case with associated data.

Figure 4-4 illustrates the overall relationship between the 32 subroutines. Subroutines INPUT and PLOT are available to all NASA computer users and are described in Appendix C. Subroutines PACK and AFRMT were written in 360 Assembler Language by R. E. Slye, the Technical Monitor of this study. Listings for each are included in Appendix D and a description of both subroutines appear in Appendix C. The remaining subroutines have flow charts in detail in Appendix C and Fortran listings in Appendix D. The first comment card in each subroutine listing states the primary purpose of that subroutine. Other comment cards describing the purpose of each section and defining any pertinent variable whose name is not mnemonic are distributed liberally throughout the listing so that new users may familiarize themselves with the logical function of each subsection within the program.

Dimension restrictions are detailed in Appendix A for input variables and for internal variables indirectly associated with the input. All other dimension constraints, data statements, and equivalence relations may be found at the beginning of the program listing for MASTER in Appendix D.

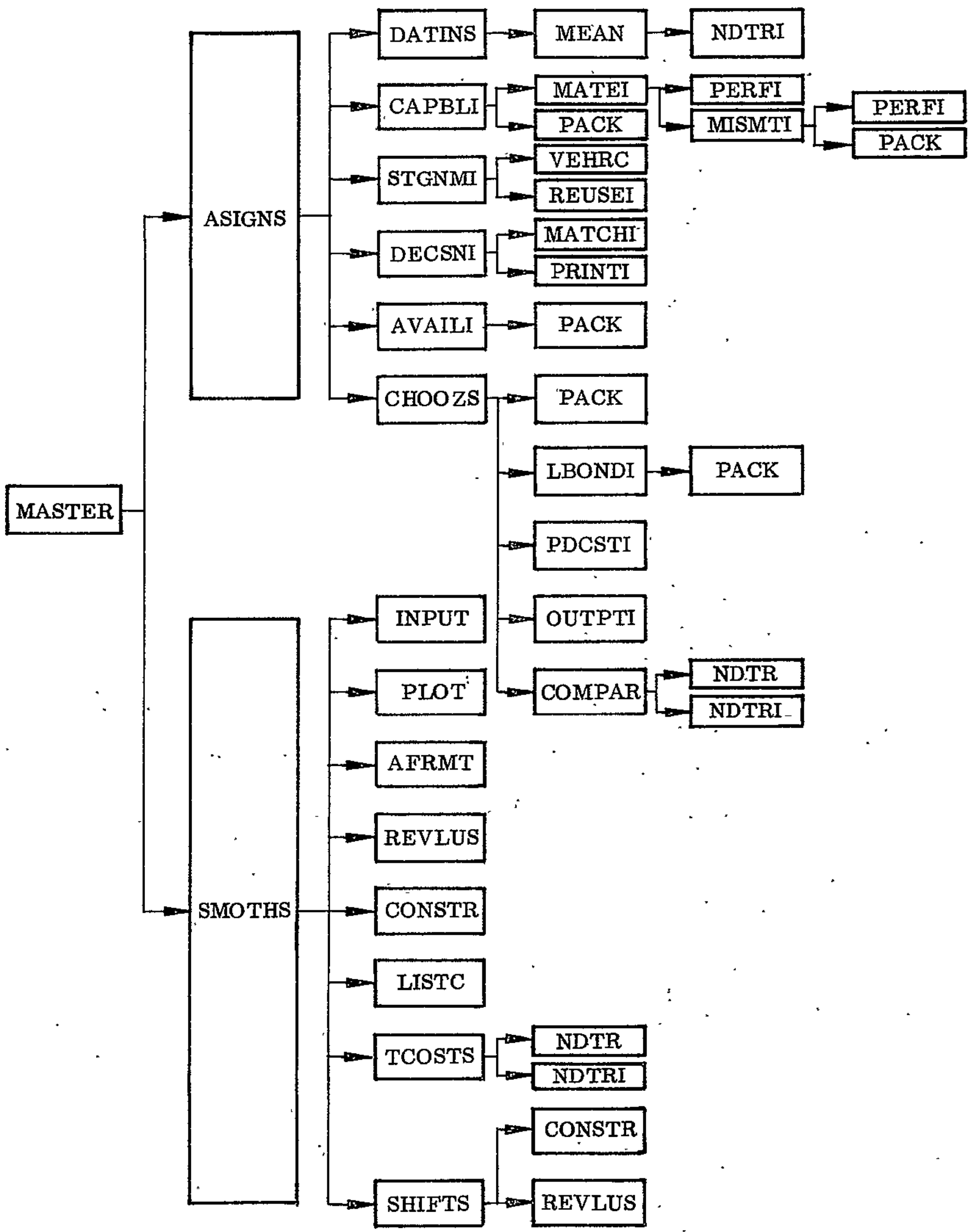


Fig. 4-4 Program Subroutine Relationships

Each subroutine has been constructed as a self-contained package with a minimum of interrelationship between routines. Consequently, any subroutine can be altered, expanded, or modified with the minimum amount of effort. The length of each subroutine was restricted so that maximum use of the Fortran H mode of compilation would result. This efficient mode of compilation results in reduced storage and reduced run times in comparison with the more common Fortran G mode.

4.2 GENERAL INPUT REQUIREMENTS

Detailed input requirements are included in Appendix A (Vol. 2). In general, cost data may be input as a most likely value (modal value) for each type, plus an xx% tail value for each type, where xx is an input value. If xx is input as zero for any cost, then the model interprets that cost as being certain so the modal value for that cost equals the expected value. If xx is zero for all cost data input (i.e., there are no upper tail values given), then the program bypasses all statistical calculations. In this manner the deterministic model reported in Ref. 1 was embedded into the present probabilistic model.

As in the deterministic model, input cost data may be related to individual stages, a family of stages, interstage integration, or launch facility. At present a launch facility is either ETR or WTR while a launch complex consists of at most three specific pads, at one of these facilities. Unit or recurring costs are expended at each launch. Fixed or one-time costs may be spread-out over a period of years, but are only spent once and must be spent before the component is considered operational. Annual costs include all sustaining-type costs, and represent any cost computed on a yearly basis. All input costs are grouped into one of these three categories, but may be related to any of the sources listed or to a particular vehicle if more convenient.

An outline of the input data which may be included in the program is shown in Table 4-1. In contrast to Appendix A, input data listed in this table is provided for the

Table 4-1

INPUT DATA

I. VEHICLE RELATED INFORMATION

A. Costs

1. Stage Name and Other Related Data

   Recurring (hardware and launch site (ETR or WTR) operations) – first unit and learning curve percent.

   Development – including the year in which development begins and the number of years over which development cost is distributed.

   Sustaining – including stage sustaining at launch site.

2. Shared Cost Data – Name of group, sustaining and development including the year in which development starts and the number of years over which the development cost is distributed.

3. Integration Cost Data (between two shared groups)

   Development – including the number of years over which the development cost is distributed and the year in which development starts.

4. Pad/Facility Costs – development and sustaining costs for stage, family, and integration. (May be input in terms of individual pads or in terms of a facility.)

5. Investment Cost for Reusable Stages

   Number of units for initial investment (May be input or program determined from the launch schedule and other reusable input data).

   First unit price.

   Amortization lifetime in terms of number of launches (optional).

   Turnaround time in days and learning curve percent (optional).

6. Miscellaneous Costs – Any costs which do not fit in the above categories

B. Performance

1. Name of stages which constitute vehicle
2. Payload vs. velocity curve constants
3. Stabilization requirement
4. Manrating requirement

Table 4-1 (Cont.)

5. Number of restarts required
6. Pad complex constraints
7. Return payload weight of reusable upper stage (input in stage section)

C. Availability

1. Final year in which the stage is available (Initial availability is assumed to be the last year of the development period).
2. Launch pad constraints, i.e., maximum rate allowed.

II. MISSION REQUIREMENTS AND COSTS

A. Mission Name, Priority, Launch Years, and the Number of Launches in Each Year

B. Costs

1. Development — including the number of years over which the development cost is distributed and the year in which development starts.
2. Recurring and four year distribution.
3. Sustaining and the number of years after the last launch date in which sustaining costs are incurred.
4. Miscellaneous — such as run-out costs. Distribution is input.

C. Requirements

1. Velocity requirement.
2. Launch site constraint, if any.
3. Payload weight either per launch or total weight to be delivered in less than NTRIP launches (input) i.e. modularization.
4. Return payload weight.
5. Stabilization requirement, if any.
6. Manrating requirement, if any.
7. Number of restarts required.
8. Number of days a reusable upper stage is required to complete mission (if appropriate).

Table 4-1 (Cont.)

III. BUDGET LEVEL DATA

1. Desired funding level for each year.
2. Calendar years for smoothing.
3. Total fixed overhead costs for each year.
4. Inflation rate.
5. Program constraints.
6. Smoothing constraint options.

non-computer oriented user. Not all data listed are necessary for a successful run. In fact the only required input is the following:

- Initial launch plus reference year and mission model duration
- At least one stage with associated recurring, development, and sustaining costs, and development year start and duration
- At least one vehicle, whose component stages have all been input, and whose performance coefficients are avilable (vehicle may be composed of only one stage)
- At least one mission with its launch rate and payload and velocity requirements (no cost data need be input for a mission)
- The desired funding level for each year and the calendar years over which smoothing is desired

All input not on the above basic list is included in order to generate complete and realistic solutions.

Recurring costs are input in terms of stage or integration costs. Any recurring costs associated with a specific launch pad are input under the associated booster recurring costs. Vehicle recurring costs are then computed by the program as the sum of all component stage recurring costs plus any applicable integration recurring costs.

Annual costs are quite complex in nature and hence require a detailed format for introduction into the program. For instance, fixed launch pad costs are launch complex oriented while annual costs are stage oriented. Annual costs are further complicated by the fact that a second pad does not require the same number of people to maintain it as the first pad. Discipline personnel are not fully utilized with only one pad and thus need not be duplicated for the second pad. However, other workers cannot maintain two pads at once, so they must be duplicated for the second pad.

Fixed costs may be entered for shared cost groups (families) or individual stages for hardware and/or launch pad expenditures. Launch facility expenditures due to integration between two stages are, in general, negligible, so this category was eliminated from consideration.

The above data is input to DATINS and CAPBLI, both subroutines of ASIGNS. Essentially only the budget levels, smoothing intervals and program constraints are now input directly to the SMOTHS subroutine. An inflation factor may be applied to all costs to be spent in the future. The anticipated budget appropriation or desired level of spending is not adjusted by the inflation factor since inflation does not directly affect the budget level. When SMOTHS is used, the budget level can be input year-by-year to reflect any growth or decline which might result from variation(s) in economic conditions. Thus, the impact of various economic effects can be defined and included in the model.

4.3 PROGRAM OPTIONS

The options available to the analyst are of two types: (1) automatically determined by the program from the data input and (2) specified directly by the user. The deterministic option explained in Section 4.2 is of type 1 since the program automatically bypasses all probabilistic calculations if all costs are deterministic. Rate effects on recurring costs are also ignored if no learning curve percentages are input. Some default options include the automatic distribution of launch vehicle recurring costs unless overridden by input to the variable ALPI, the automatic input of zero to most applicable budget items unless overridden by actual input, and the automatic use of the extension and acceleration options in the smoothing section unless FALSE is specified for the variables EXT or ACCL respectively. If NSOL (the number of solutions to be output in ascending order of total program cost), is input as zero, one optimal solution will still be found.

There are four major options which must be specified by the user – LP, MOS, NOPT, and NU.

4.3.1 LP Option

The first such option is the code for logic printout. In a test run code LP = 2 should be used so that the internal logic may be checked for accuracy. Many lines

of output are required, however, so this option should not be used in general. If LP = 1, suboptimal solutions may be traced in the branch and bound logic and the optimal solution justified step by step. Thus, reasons for selection or non-selection of a program element in an assignment may be determined in detail if desired. LP = 0 is the normal mode for production runs. Only final solutions and characteristics of these solutions are output under this last option.

4.3.2 MOS Option

In order to accommodate some of the various uses which the analyst may have for the model, four options are made available to the user. On the first data card, the user specifies which option he desires by an appropriate value for MOS (method of solution).

MOS = 0	Optimize launch vehicle assignment and smooth the resulting budget within constraints input to SMOTHS
MOS = 1	Input specific launch vehicle assignment and smooth the resulting budget
MOS = 2	Optimize launch vehicle assignment and output associated costs by year and program (do not smooth budget)
MOS = 3	Input specific launch vehicle assignment and print out associated costs by year and program

Thus the optimal assignment program without smoothing is available using MOS = 2, the smoothing program alone using MOS = 1 and the integrated program using MOS = 0. MOS = 3 is useful in testing assignments derived from outside sources. Total cost distributions are then available for these assignments which may be compared to previously found optimal assignments.

4.3.3 NOPT Option

The mission/vehicle compatibility screen may be in one of three forms. The basic screen (NOPT = 1) consists of first looking to see if there is an a priori vehicle

assignment. If there is one, all other vehicles are excluded from consideration for that mission.

If there is no such pre-assignment, the payload capability of the vehicle is compared to the payload desired for each mission at the required characteristic velocity. Modularization is taken into consideration in determining whether the launch vehicle can or cannot accomplish the mission. The availability of each vehicle for a particular mission is determined later in subroutine AVAILI, where a final compatibility matrix is output.

If NOPT = 2 is specified, the basic screen above is applied to any vehicle input directly and to all vehicles formed in the stage-matching screen performed in subroutine MATEI.

If NOPT = 3 is specified, the basic screen is augmented by tests on the stabilization, man-rating and other requirements input on the mission card. If NOPT is not specified as 2 or 3, then the basic screen is the default option.

4.3.4 NU Option

NU, the number of reusable units to be purchased, is zero if the stage is expendable. However, if the stage is reusable then either a positive number is input to NU and this number is used directly by the program throughout all iterations, or a negative number is input to NU and then the program uses this estimate for the first iteration but calculates its own estimate based on actual usage for succeeding estimates. The program estimate is based on turn-around-time, amortization lifetime, and mission use time, as appropriate. The estimate is calculated in subroutine REUSEI (the logic flow diagram is in Appendix C, Vol. 2).

Other options such as using the Beta distribution or an alternative input distribution for any development cost are explained in the comment section of Appendix A (Vol. 2) Input Requirements.

4.4 SMOOTHING CONSTRAINTS

Constraints are input directly to SMOTHS for missions and for miscellaneous programs having no associated launches. They are keyed according to the following table where:

KODE = the type of constraint by key number (see Table 4-2)
NPROG = N = the constrained program reference number
KPROG = K = the constraining program reference number
CS = associated real number constant

Table 4-2

KEY TO PROGRAM CONSTRAINTS[a]

KODE	
1	$START_N > END_K + CS$
2	$END_N + CS < START_K$
3	$START_N = CS$
4	$END_N = CS$
5	$DEV.\ DURATION_N = CS$ (FIXED DURATION)
6	$LAUNCH\ DATE_N + CS \leq LAUNCH\ DATE_K$
7	$LAUNCH\ DATE_N \leq CS$
8	NO CHANGES ALLOWED
9	$START_N \geq CS$
10	$LAUNCH\ DATE_N \geq CS$
11	$END_N + CS < LAUNCH\ DATE_K$

(a) START and END refer to development.

Input program data must satisfy the input constraints to ensure a correct output from SMOTHS. Any violations in input data are printed out before "smoothing" begins so that the user is aware of the condition. The program will continue even if violations occur since in many cases the violations are corrected by the "shifting" process.

Costs associated with launch vehicles in the optimal solution are automatically constrained in MASTER. KODE 11 is used to ensure that all development programs selected by ASIGNS in the optimal solution end before the component being developed is to be launched. Thus, SMOTHS is automatically constrained so that the optimal vehicle assignment input to SMOTHS is still a feasible candidate assignment after SMOTHS is complete. Whether the assignment input to SMOTHS is still optimal depends on which variables have been "shifted" by SMOTHS. If key variables have been changed, ASIGNS is called to again determine the optimal assignment. Depending on the effect of the "shift" changes, this new optimal assignment can be the same as the previous assignment or it can be different.

Even if the shift constraints imposed on SMOTHS prevent the smoothing of an optimal assignment into one which is less than the budget level, the program will still output an optimum assignment; however, in this case the root-mean-square cost difference between the actual spending level and the imposed budget level will be larger than if less constraints had been imposed.

4.5 OUTPUT

A sample output is presented in detail in Appendix B (Vol. 2) and some of the analytic relationships to be output were discussed in section 3.4. This present section will briefly cover the output from this program and section 4.6 will discuss how this output may be utilized.

First, all the input data are output for reference, including data computed by the program which will be input to the ASIGNS algorithm. Both input modal values and computed expected values are output whenever appropriate. Then the optimal assignment is output listing each mission and the assigned optimal vehicle, along with total mission model cost. If NSOL is greater than one, each assignment in ascending order of expected total cost is output until NSOL solutions have been found. For each assignment, the log-normal distribution describing the uncertainties associated with its total

cost is output along with its modal (most likely) value and 50% uncertainty interval. Each assignment is compared to each preceding one in order to determine the probability that it will cost more than the one preceding, given a definite correlation between assignments.

Input to SMOTHS is output automatically as it appears on the data card. "Average" recurring cost data for each vehicle in the optimal assignment is computed in VEHRC. This cost is determined by totaling the actual recurring costs of all program elements associated with each vehicle over the entire mission duration and then dividing by the total number of vehicles used throughout the mission model. The constraints input to the program and those calculated in MASTER are output for reference. Any violations to these constraints in the input data are noted. Finally the cost data comprising the optimal assignment that is input to SMOTHS is output by program and type and also by year. A plot showing expected spending by year and desired spending level by year follows. The most likely (modal) spending level by year and the upper bound on a 50% confidence interval are also included on the plot.

The program then smooths this input data and outputs the final result in the same form as it did the input data. Launch vehicle requirements by year are output using the smoothed data. At this point the program either terminates because an optimal smoothed assignment has been found or else it returns to ASIGNS and outputs the new data which will be used in the algorithm. The output cycle then continues as explained above until an optimal solution has been found.

4.6 PRODUCTION RUNS AND SENSITIVITY ANALYSES

Extensive production runs have been made using the deterministic version of this model to checkout logic on a large-scale basis. As budget levels were allowed to vary parametrically, the mission models varied accordingly until a "smoothed" solution could be found for each case. The type of mission to be included in any future mission profile can be specified by the analyst; however, some mission types may be shown to

be too expensive for realistic budget levels through use of this program. Since the least cost total space program which accomplishes the mission model is always selected by the program for budget analysis, the mission model is the only variable which needs to be modified as the budget level varies.

Logic checkout runs for the probabilistic model were similar in nature to the production runs made earlier. Due to the fact that the probabilistic model optimizes on expected costs, while the deterministic model optimizes on most likely costs, the solutions from each model will not necessarily be the same. Therefore in analyzing a program it may be desirable to make runs on both the statistical and deterministic models in order to compare solutions and identify any dominant factors that are influencing the selection of the optimal assignment.

As an example Fig. 4-5 demonstrates one sensitivity tradeoff which may be made using output from the model. One NASA mission profile was fixed and runs were made using various projected reusable vehicles and several expendable vehicles as candidates for assignment. One set of runs were made on the deterministic model, varying only the number of launches over a 10-year period. A similar set was then completed on the probabilisitc model. For the example input data used in this case, the least cost vehicle for this mission model consisted of an expendable lower and second stage with a reusable upper stage if the launch rate was less than 110 over 10 years for the deterministic model. For the probabilistic model the critical launch rate was found to be 190 over 10 years.

That is, the transition to the optimal assignment of an (ultimately) less costly candidate system (i.e., from expendable vehicle 1 + a reusable spacecraft to the partially reusable launch vehicle 2) occurred at line A (110 launches/10 yr) for the deterministic case, and at line B (190 launches/10 yr) for the probabilistic case. This variation in transition occurs because the uncertainties in the costs of the partially reusable system are large in comparison to the relative certainty of costs associated with an upgraded existing vehicle.

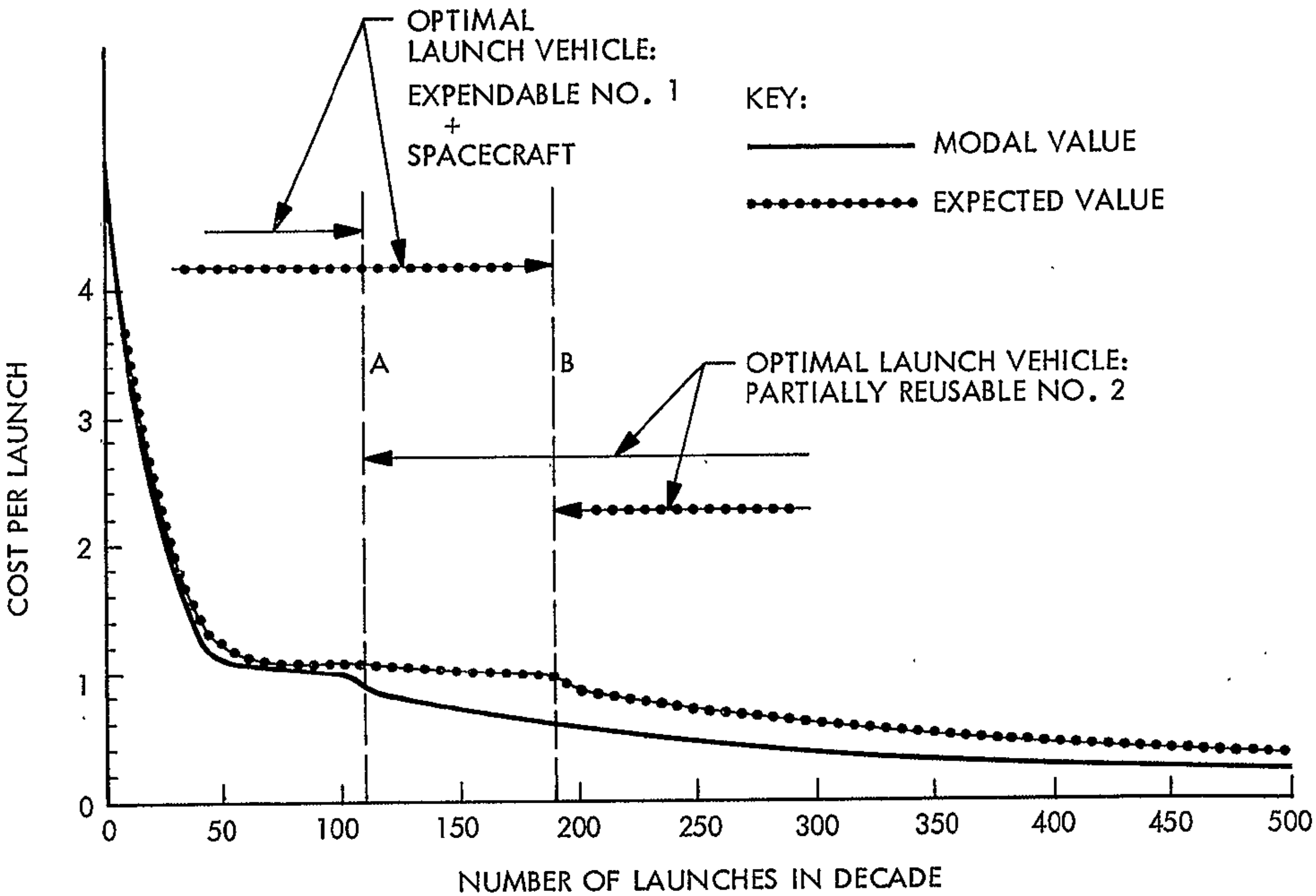


Fig. 4-5 Optimal Launch Vehicle Sensitivity Analysis

Also as indicated by the two curves in this figure, for positively skewed distributions, determined to be typical of advanced technology space programs based on the analysis in Section 2, the expected (mean) value will be greater than the model value. This difference derives from the fact that in high technology programs, which typically have cost growth factors of two or more, there are a significant number of programs with quite high cost growths. This situation produces a long tail on the distribution and an expected value greater than the mode. The expected value is a more realistic cost estimate than the model value for these advanced programs since it corresponds to the center of gravity of the distribution.

The capability of the probabilistic model to output expected value outcomes and also outcomes that can be quantified to any degree of certainty is indicative of the effectiveness of this new tool. The necessity for more effectively handling the cost uncertainties in advanced technology systems by using a probabilistic approach has received recent emphasis (Ref. 18).

As indicated, the analysis illustrated in Fig. 4-5 was made with a fixed mission model. By varying this mission model, sensitivities to mission requirements may also be determined. These examples are some of the many sensitivity analyses and other tradeoffs which can be made using the probabilistic computer model.

The extensive flexibilities inherent in this model, its capability to quantitatively evaluate the uncertainties known to be present in advanced space program costs, and the ability to quantify outcomes to any degree of certainty provide the user with a unique evaluation tool.

Section 5
CONCLUDING REMARKS

5.1 PROBABILISTIC MODEL DEVELOPMENT

Prior analyses of historical data and analyses performed during this study have clearly shown that there are predictable undertainties in data applicable to advanced development space systems. This variability is particularly evident for costs in areas that have technological risk and under economic conditions which can change during a system life cycle.

Under these conditions of variability, a probabilistic model is an essential tool for providing quantitative evaluations for space systems and over-all programs. The need for a probabilistic approach to problems of this type has recently been emphasized (Ref. 18). This present work provides NASA with a unique and advanced tool in this problem area.

Building on a previously developed deterministic model, during the present study effort the space program optimal assignment and budget smoothing model was converted to a probabilistic model. Check-out runs with this model have been performed.

5.2 SUMMARY OF RESULTS

The following include key results of the study and outline significant capabilities of the probabilistic computer model. Details are provided in the body of this report.

5.2.1 Primary Result

The development of a comprehensive space program evaluation tool is a primary result of this study. Using a significantly modified branch-and-bound technique for

accelerated search, the model quantitatively evaluates all combinations of launch vehicles and other interrelated space program elements to output a global optimum, least cost total space program over a one to 20 year period. The model retains the capability for deterministic solutions but adds the new, powerful dimension of probabilistic evaluations and sensitivity analyses, which quantify the cost uncertainties known to exist in high technology, advanced space programs. Based on the statistical input, the model can provide output data quantified to any degree of certainty.

5.2.2 Data Analysis

The analysis of historical data accomplished the following:

- Provided a basis for analytic solution based on probability distributions rather than random number methods. This reduced solution complexity and retained short program run times.
- Identified the log-normal distribution as the most appropriate type for advanced systems having technology risk.
- Provided preliminary values for statistical input parameters.

5.2.3 System Performance

The model handles launch vehicle and related element physical characteristics, functional performance, and time availability.

5.2.4 Flexibility

Multiple options for data input, internal analyses and output options provide flexible adaption of the model to the needs of the analyst.

5.2.5 Range of Problems Solved

The model can be applied to a broad range of space program evaluations. These extend from macro-problems that evaluate various options of total space programs, to intermediate problems which analyze selected categories of space programs (e.g.,

optimizing the scientific, exploratory, service satellite category within a total space program), and to micro-problems (e.g., determining the cost optimal subsystem among several alternates for a given space vehicle).

5.2.6 Production Use

The model has retained storage minimizing features and short run times. These permit program use in a multi-user computer system.

5.2.7 Optimal Assignment and Budget Smoothing

The model retains the capability for optimal assignment of program elements. These assignments can be smoothed between parameterized, year-by-year budget constraints and support bases, and under varying external economic conditions including growth and inflation.

5.2.8 Growth Potential

The model is structured with independence between subroutines whenever feasible. This independence permits the addition of subroutines as required to extend its capability with minimum interaction. For example orbit-to-orbit maneuvering capability can be easily added to reflect characteristics of increased importance of this capability in future systems.

Historical data analysis has provided preliminary values for statistical parameters for initial model use. Further analysis is desirable to more firmly quantify statistical parameters including cost growth, particularly in the upper tail region, and correlation between variables.

Multi-dimensional output plots which bound certainty regions will provide quicker reaction capability and more lucid output. The use of cathode-ray tube output display will provide increased capability in both of these areas.

5.2.9 Versatility

The model provides for analyses of expendables, partially reusables, and fully reusables within a total program mix. Evaluations and sensitivity trade-offs include the effects of uncertainty in all such analyses.

5.2.10 Applications

Because of its versatility this unique tool has broad application to diverse space program evaluation and sensitivity analyses. Two model applications which supplement its primary use are suggested.

- Since output can be bounded by certainty regions based on historical data, more realistic outcomes are available for program estimates, evaluations, and tradeoffs. One use can be the detection of "buy-in's" and a basis for better quantified program control in the development of advanced systems.
- The identification of new space program directions that link the space program to substantial national requirements, and that can develop substantial growth and show a profit over the long term.

In the present study the developed methodology and the optimal assignment model applies to space systems. However, the technique can be readily applied to diverse optimal combinatorial problems by particularizing the parameters to the new problem.

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